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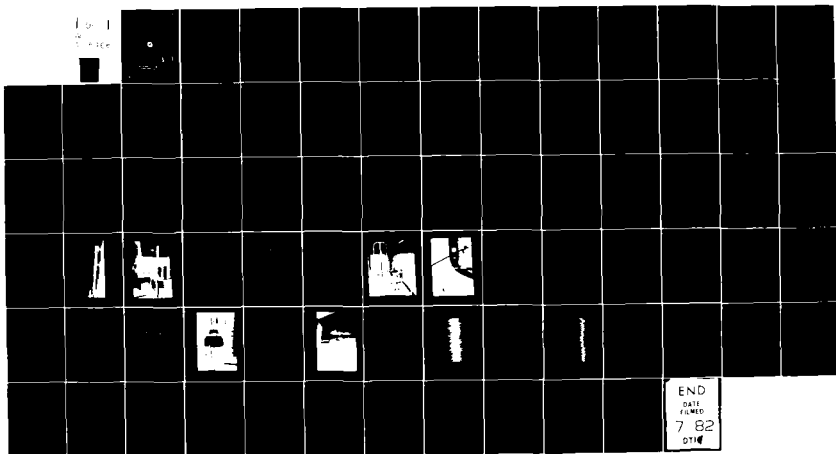
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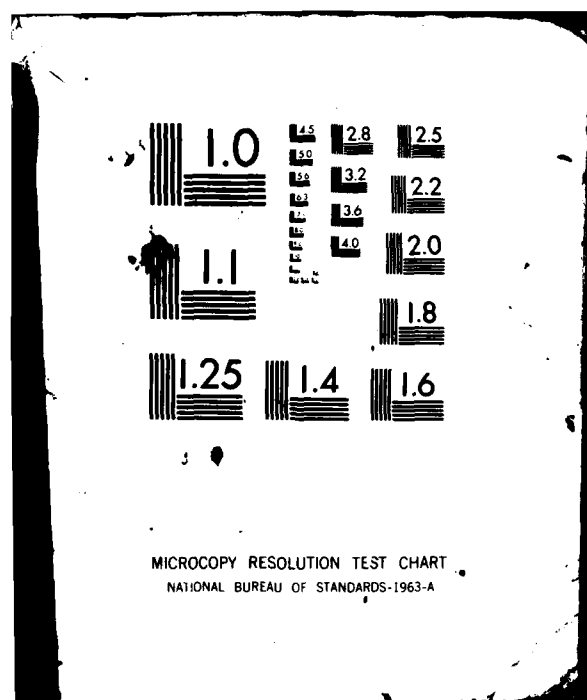
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# SPRINGING RESEARCH OF A GREAT LAKES ORE CARRIER

DAVID A. WALDEN

MARK D. NOLL



Final Report

April 1981

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## Technical Report Documentation Page

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16. Abstract This report discusses the springing research of ore carriers, which has been going on in the Great Lakes from the early 70's to the present. Springing Research undertaken by the Coast Guard is presented, covering very early data collection, analysis and problems, and extending to the present. The object of this research is to fully understand the structural response of Great Lake vessels especially those 1000 feet and longer, to insure adequate longitudinal strength. To obtain the structural response, the hull stress and wave height are measured. the relationship of these two parameters defines a Response Amplitude Operator (RAO). The RAO gives an accurate description of the out-of-phase/in-phase characteristic of the seaway with the hull response in terms of hull stress. The authors have determined the RAO's of a 1000 foot long GL vessel and show graphically how the determined RAO's compare with the theoretically computed RAO's of the American Bureau of Shipping (ABS), Webb Institute of Naval Architect, the University of Michigan (UM) and Det norske Veritas. The weaknesses of these carriers may be critical. The ABS and USCG longitudinal strength standards agreed upon for the Great Lakes ore carriers at the present, were based upon all the available research results up until 1978. Since 1970, Great Lake bulk carriers have increased in length by up to 50% and carry up to 5 times the cargo of the smaller carriers of the past. This report concludes with how the authors intend to follow up this work with future data collections and ultimately arrive at some specific conclusions concerning wave induced and springing stresses and how they combine on a 1000 foot Great Lake ore carrier. This work will aid in determining the construction standards for future Great Lake ore carriers.			
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# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yds	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
sq in	square inches	6.5	square centimeters	cm <sup>2</sup>
sq ft	square feet	0.09	square meters	m <sup>2</sup>
sq yds	square yards	0.8	square meters	m <sup>2</sup>
sq mi	square miles	2.6	square kilometers	km <sup>2</sup>
acre	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
short ton (2000 lb)	short tons	0.9	tonnes	t
<b>VOLUME</b>				
cc	cubic centimeters	1	milliliters	ml
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
cu ft	cubic feet	0.028	cubic meters	m <sup>3</sup>
cu yd	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
F	Fahrenheit temperature	$(F - 32) \times \frac{5}{9}$	Celsius temperature	C

\* 1 in = 2.54 exactly. For other exact conversions and more detailed tables, see NIST Spec. Publ. 280, *Units, Symbols, and Abbreviations*, NIST Monograph 99, 80 Coding No. C13.10-280.

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	ac
<b>MASS (weight)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
<b>VOLUME</b>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m <sup>3</sup>	cubic meters	35	cubic feet	cu ft
m <sup>3</sup>	cubic meters	1.3	cubic yards	cu yd
<b>TEMPERATURE (exact)</b>				
C	Celsius temperature	$(C \times \frac{9}{5}) + 32$	Fahrenheit temperature	F



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Springing Research on a  
Great Lakes Ore Carrier

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The opinions expressed herein are those of the authors and do not necessarily reflect those of the U.S. Coast Guard.

Abstract

During the fall of 1979 and 1980, the M/V STEWART J. CORT was instrumented to simultaneously measure wave heights, midship stresses, pressures at the bow, and ship motions. Measurements were made during normal operations in Lakes Superior and Michigan. Of particular interest to the Coast Guard have been the high stresses that a Great Lake ore carrier experiences from the combined effects of static, wave-induced, and high frequency springing loads. Springing has been especially evident in Great Lake ore carriers having a long length and shallow depth (where  $L/D = 20$  or  $21$ , natural frequency =  $.33$  Hz, ship speed =  $12$  to  $15$  MPH).

This paper discusses Great Lakes springing research, instrumentation for data collection of the M/V STEWART J. CORT and helicopter-buoy operations. Preliminary analysis of the data has included spectral and time history analysis. During the preliminary data analysis phase, RAO's (response amplitude operators) were developed and compared with theoretical RAO's computed by American Bureau of Shipping (ABS), Webb Institute of Naval Architecture, the University of Michigan (UM) and Det norske Veritas (DnV). The initial comparisons do not completely agree and they indicate that the springing phenomenon is not completely understood.

The objective of this research is to fully understand the structural response of Great Lakes vessels, especially those 1000 feet and longer, to insure adequate longitudinal strength.



## Introduction

Interest in the springing of Great Lakes ships is not confined to the USCG. Springing related research includes work by the United States Coast Guard (USCG), the Ship Structure Committee (SSC), David Taylor Naval Ship Research and Development Center (DTNSRDC), the American Bureau of Shipping (ABS), Stevens Institute of Technology (SIT), Bethlehem Steel Corporation, Webb Institute of Naval Architecture, and the University of Michigan (UM), the Maritime Administration (MarAd), and Det norske Veritas (DnV). The primary purpose behind this research has been to improve operational safety for the vessel and crew by preventing catastrophic loss of ship and lives due to inadequate longitudinal strength.

The continuation of measurements on board M/V STEWART J. CORT (sponsored by USCG) and springing model experiments at the University of Michigan (sponsored by ABS-MarAd) are the major currently ongoing research projects. The complete scope of hull stress related projects include:

- (a) research into springing excitation and response including measurements for validation (NRL and DTNSRDC; sponsored by USCG)
- (b) theoretical and experimental research on the combination of springing and wave-induced bending (SIT; sponsored by USCG)
- (c) calculation and measurement of structural and hydrodynamic damping (SSC and USCG)

Item (a) above has been the primary concern of the USCG Research and Development program and is the subject of this paper. Areas of concern include: (1) measuring the actual sea conditions, (2) measuring vessel response and motions, (3) determining the structural, cargo, and hydrodynamic damping coefficients to determine the total system damping, (4) measuring hydrodynamic pressures, and (4) analyzing the measured data including comparison with analytical predictions.

Continuing research in these areas will provide the technical basis for higher confidence in the longitudinal strength standard for Great Lake vessels over 750 feet in length. A better understanding of the structural load/response relationship will aid in building a "strong" yet "economical" ship. Additionally, technical knowledge of

the relationship between the loads and the structural response will provide a broad knowledge base for advancing the art of designing ships capable of withstanding wave loads in a dynamic and complex water environment.

The direct benefits to be derived from this complete program are:

- (a) a technical basis on which to raise or lower load line requirements
- (b) design review will address the ability of the vessel to withstand all imposed loads
- (c) aging Great Lakes carriers may be reanalyzed from a safety point of view as theoretical prediction techniques are improved and verified
- (d) advanced seaway measurement capability will aid Masters in operating their vessel more effectively and safely
- (e) the design of larger vessels will account not only for static loads but also for springing and wave-induced loads

#### Section Modulus

The Load Line (LL) Regulations define the required section modulus for Great Lakes vessels as the function  $SM = fdB$ .

SM - Section modulus

f - a factor obtained from a LL Table

d - the molded draft, ft

B - the molded breadth, ft

The LL Regulations define f for Great Lakes vessels in which L/D does not exceed 13.5 for vessels 325 ft or less and 19.0 for vessels 600 ft or more. Intermediate values are found by interpolation. The value of f for Great Lakes vessels is generally smaller than for ocean going vessels because:

- (a) fresh water density (36 cu ft/ton) is less than for salt water (35) which reduces the static and dynamic strains on Great Lakes vessels.

- (b) lesser corrosion rate in fresh water which reduces need for additional shell thickness
- (c) Great Lakes vessels seldom encounter wave lengths equal to the own length which causes BM to be less than for ocean ships

As a result, the LL regulations specify a minimum freeboard (and therefore maximum draft) which then fixes the required SM for a vessel of given length, beam and depth. But these requirements are adjustable where service requires less draft than that required by minimum freeboard. This results in a reduced SM. Similar reductions are allowed in deck and shell thickness with a reduced draft but are limited by a minimum required scantling draft.

The research on the Great Lakes vessels is tackling the SM questions for long ships since the L/D ratio now ranges between 20 and 22. This is greater than the L/D of 19.0 described in the LL Regulations. These vessels are experiencing stresses composed of wave induced and springing stresses. The question remains: can the SM for large ore carriers be found simply by extrapolation of the rules to develop new values of  $f$  that are satisfactory or must a new empirical formula be found based on full scale, model and theoretical experiments?

### Springing

Springing is a two-noded vertical vibration of the vessel's hull structure. When the ship-wave encounter frequency matches the natural frequency of the hull girder, springing can result and may cause high alternating stresses (i.e. tensile to compressive) which, if combined with high static and wave-induced stresses, may momentarily overstress the vessel and, if continued, may cause structural damage.

Springing has been especially evident in Great Lake ore carriers having a length to depth ratio of  $L/D = 20$  or  $21$ . One such vessel is the M/V CORT which is a 1000 foot, 60,000 DWT, ore carrier traversing the Great Lakes between Superior, Wisconsin and Burns Harbor, Indiana. The principle characteristics and hull form data for the M/V STEWART J. CORT, Figure 1, are given in Table 1. The natural frequency for this vessel is about 0.33 Hz. Operating in head seas at a speed between 12 and 17 MPH, the vessel may encounter wave lengths of 100 feet creating

an encounter frequency which may induce springing and cause large bending moments. The ship dimensions give the hull girder the characteristics of a long, flat cantilever beam with a low frequency response and a high displacement response when excited by an external force. Vessels with lengths over 750 feet LOA are becoming common. The largest vessels are now 1000 feet LOA with new designs being proposed for 1100 feet LOA. The beam and depth of these vessels are restricted by the dimensions of the locks at Sault Ste. Marie. The largest lock is 1200 feet long by 110 feet wide with a draft over the sills of 32 feet at low water datum.

Springing also occurs in ocean going vessels. However, the ocean vessel of similar length has greater beam and depth than the Great Lakes vessel and a greater SM requirement as discussed above. Therefore the resulting bending moments and stresses for ocean vessels are generally handled by increased scantlings for ocean vessels. Also, the properties of Great Lakes waves are known to differ from those of ocean waves. The limited fetches on the Lakes mean that waves are not as large as in the open ocean and that they never reach their fully developed state. This means that the long waves never have a chance to build and leads to the short, steep waves generally accepted as characteristic of the Lakes.

The complexity of a vessel's structure magnifies the difficulty in studying structural response of a vessel in a seaway. Equally complex is the measurement of the dynamic seaway in which a vessel must operate. The combination of the two areas increases the difficulty in determining structural loading design criteria.

#### M/V STEWART J. CORT

The CORT was delivered to service in 1972. The original design was by Litton Industries and the final design by Marine Consultants and Designers, Inc. The bow and stern of the CORT were built by Ingalls Nuclear Shipbuilding in Pascagoula, Mississippi. The bow and stern section sailed from Mississippi to Erie, Pennsylvania, where Erie Marine added the 800 foot parallel midbody and increased the beam by 30 feet. The CORT has twin screws, twin rudders, and bow and stern thrusters.

The SM of the midship section was originally designed with the fdB longitudinal strength requirement (see Section Modulus above) with 10% increase factored in as an extrapolation of the f tables in the LL Regulations. The SM formula thus read as  $fdB \times 1.10$ .

The CORT has a design draft of 25'-9". However, because of the expectation of increased lock sizes and channel depths, the actual scantlings were sized at a 32'-6" draft and a depth increase from 47 to 49 feet to accomodate the possible increase in draft.

Longitudinal frame spacing is one-third plate width (approximately 27"). Web frame spacing is 8 feet with 42" depth, which was a concession from the original 6 foot spacing, 30" depth. ABS approved this change based on structural similarities between the CORT and existing tanker construction and the lack of Lakes rules to cover this length vessel and the desire to increase the vessel's torsional rigidity.

The upper and lower flanges of the hull girder and the plating between hatches (48 foot hatch spacing) used high strength steels. Further detail on the construction, structure, and machinery of the CORT can be found in Reference 1.

#### Past USCG Springing Research

##### 1. Experimental and Theoretical Evaluation of Springing on a Great Lakes Bulk Carrier (Reference 2)

Experiments were carried out at Webb Institute on a model of the Great Lakes bulk carrier, M/V STEWART J. CORT, joined amidships, with four different connecting beams. These beams provided different degrees of stiffness with different natural frequencies of vertical hull vibration. Springing was simulated in short regular waves generated in a model tank at various resonant combinations of model speed and wave length. At equal speeds the effect of increasing stiffness was found to be a decrease in the magnitude of springing at resonance when expressed as bending moment relative to wave slope.

Concurrent theoretical calculations also determined springing to be extremely sensitive to the level of damping introduced. Both theory and experiment showed trends which were in good agreement. If appropriate assumptions were

made regarding damping, good agreement was also obtained in magnitudes of springing bending moments.

## 2. 1973 Instrumentation of the CORT (Reference 3)

Teledyne Engineering Services (TES) (formerly: Teledyne Materials Research Corporation), instrumented the CORT between 1971 and 1975 to study the bending stresses experienced by the vessel during normal operations. The vessel was instrumented with five sets of strain gauge transducers, a metritape liquid-level sensor to measure wave encounter periods, bow and stern vertical accelerometers, a pendulum located near the center of gravity for measuring pitch, and a data recording system.

During the 1973 season, 18 reels of magnetic tape containing 795 basic underway data intervals of one half-hour or more were collected on board the CORT. Less than 5 percent of these data intervals contained bending stresses exceeding 7,500 psi peak-to-trough. Under storm conditions, however, stresses occasionally exceeded 20,000 psi, peak-to-trough and during the gale of May 2, 1973 a peak value of 29,400 psi was recorded. Table 2 (extracted from Reference 3), gives the maximum combined, wave induced and springing stress values obtained during four storms encountered during this period. Note that in storms 1 and 4, the maximum springing and wave induced stress are almost equal. Occuring independently, these stresses are not of major concern. When combined, the values approach 30 kpsi or higher, which begins to be of some concern.

## 3. Springing Stress Analysis from SS BEEGHLY and M/V CORT (Reference 4)

The David Taylor Naval Ship Research and Development Center (DTNSRDC) was tasked by the U. S. Coast Guard in 1974 to analyze midship deck bending stresses of two Great Lakes ore ships, the M/V STEWART J. CORT and the SS CHARLES M. BEEGHLY, for a two year period of operation. (References 5 and 6 describe the data collection project and an earlier analysis respectively.) In the analysis, DTNSRDC noted a slight trend for the springing stress levels to increase with increasing sea states. The most severe conditions were during heavy weather when the combination of springing and wave bending stresses resulted in a hull stress range of up to 30,000 psi.

An indicator of how the springing and bending components combined was given by the fraction  $U/(S+W)$ . U was the unfiltered maximum value in an interval, S was the maximum springing value, and W was the maximum wave bending value. In the 8 to 12 minute samples examined, this fraction varied from 0.74 to 0.96 using peak values measured from the mean. The most frequent value of the fraction was 0.87. Although the combined signal was normally less than the sum of the components, there are some instances where the two components peaked at the same time resulting in a "fraction" of 1.0. When this occurs, the concern is that the peak springing stress may be occurring simultaneously with the peak wave induced stress. However, in most cases the maximum springing amplitudes did not occur during the same intervals as the maximum wave bending.

The power spectral density plots developed by DTNSRDC indicated that the springing energy always occurred at nearly the same frequency. The wave bending frequency would be expected to vary with sea conditions although the samples examined did not show much variation. The RMS value of the unfiltered signal was approximately the square root of the sum of the squares of the RMS values of the two components since there were not normally significant components at higher frequencies.

The measurements did not include a means to measure wave height other than the metri-tape liquid level sensor, which eventually proved to be inadequate. This was another drawback in that the data analyzed did not include an adequate basis for evaluating the sea conditions.

#### 4. Applying Springing theory and Experimentation to Design Standards (Reference 7)

The problem of springing on Great Lakes ships involves two aspects: (1) the development of a satisfactory theory for calculating the springing bending moment and verifying this theory by comparison with model tests and full-scale data, and (2) the use of the theory to determine a midship section design standard.

To address this need, an international panel, the Joint Technical Committee on Great Lakes Load Lines, conferred in Ottawa in the Spring of 1967. The committee's work resulted in the formulation of a strength standard which, together with its subsequent modification, was adopted by

the conferees on an interim basis in 1968. It specified section modulus requirements on the basis of combined effects from still water, wave bending and springing moments. It was always intended as an interim standard that would be replaced if and when sufficient new information became available. In 1975, the 1968 Ottawa longitudinal strength standard was still in use on the Great Lakes. The basis for the standard was a theoretical treatment of the ship hull as a vibrating beam.

A Proposed New Approach was generated through theoretical work performed at Webb and supported by model tests in their tank. In particular, the linear theory developed suggested that the springing bending moment was proportional to the first rather than the second power of the resonant wave height. A non-dimensional bending moment and a non-dimensional bending moment coefficient were proposed. When results of the Proposed New Approach were compared with the Ottawa 1968 standard, only the trends developed could be considered because the quantitative level of calculated results were based on the limited number of available Great Lakes spectra. The comparative curves were based on the value of coefficient corresponding to the average highest in 1000 cycles of springing and if a larger or smaller value is selected, the curves may move upward or downward. Questions still remained regarding the wave spectra to be used, the characteristic response (i.e., highest in 1000 or other), and the manner in which wave bending and springing bending moments were to be combined. An important conclusion reached was that further statistical study of wave spectra should be carried out before attempting to arrive at a final standard.

#### 5. American Bureau of Shipping Strength Standard (Reference 8)

A reevaluation was needed of the ABS longitudinal strength requirements for ships operating in the Great Lakes and Gulf of St. Lawrence since ABS Rules, "Rules for Building and Classing Bulk Carriers for Service on the Great Lakes", concerning section modulus were limited to lengths of 850 feet. These Rules did specify a minimum thickness for the scantlings of bottom and side shell for ship lengths up to 1000 feet. Further consideration had to be given to new vessel designs with lengths up to 1400 feet. ABS gave careful consideration to the extrapolation of strength requirements for these longer and larger ships from past experience with shorter vessels.



As in the 1966 ABS Rules and the 1968 Interim Standard, this study proposed a minimum section modulus, formulated as a function of ship length, as the primary indicator of longitudinal strength. ABS established a two-parameter longitudinal strength standard for determining SM and developed a formula for the combined dynamic moment which was a function of wave-induced and springing bending moments. Further detail on this development may be found in Reference 8.

ABS concluded that further work was still needed, particularly in quantifying extreme stress levels in severe weather. Very little data had been collected for significant wave heights greater than 22 feet. Further work was needed to document and verify extreme wave heights. The study also concluded that further work was necessary to fit theoretical spectra to available measured data.

The American Bureau of Shipping and the US Coast Guard agreed upon of a set of interim rules for Great Lakes bulk carriers in March 1978. The requirements, which account for both the wave-induced and springing loads, are based on all the available research results of the past ten years. It still had several possible weak areas which the current research is attempting to either satisfy or strengthen. These weaknesses may be critical because, since 1970, Great Lake bulk carriers have increased in length by up to 50% and carry up to 5 times the cargo of their predecessors. This amounts to a quantum increase with definite questions as to whether previous experience with smaller vessels is adequate to judge larger vessels.

Upon the completion of the rule development, it was then the mutual understanding between the Coast Guard and ABS that further research would be necessary to verify and to validate the analytical method for predicting the response of the hull structure to springing.

## 1978 - 1980 USCG Research

In an effort to build upon past research, the USCG has undertaken a multi-phase program to obtain a more thorough understanding of springing. The approach taken has been to (1) develop a system for measuring waves from on-board an operating vessel, (2) instrument a vessel with a wave measurement system for a test and evaluation, (3) add a stress measurement system to record stresses and waves simultaneously for comparison of the wave spectra and the response spectra, (4) add a pressure measurement system, and (5) perform a full analysis and evaluation of the collected data.

During the development of the program, it was noted that past attempts at data analysis of stress measurements were often hindered by the fact that data analysis usually did not occur until long after the data was collected. The data acquisition system incorporated into this project enables the researcher to perform an analysis of the data while on-board the vessel and thus avoid the not uncommon two to three year delay in data analysis. In this way, the accuracy of the data may be checked minutes after the data has been collected.

### Wave Measurement Device Survey

In 1976, Naval Research Laboratory (NRL) was contracted to perform a survey of existing wave measurement devices capable of measuring wave height and direction. NRL took into consideration the conclusions and recommendations reached by Dalzell (Reference 9). As a result, NRL recommended (1) replace the marine radar on the CORT with a Raytheon model 1020 marine radar which would provide the wave images necessary for determination of wave length and wave direction via a laser fourier transform using an optical processor and (2) install a Collins Radio Co., radar altimeter for measuring wave height (Reference 10). The USCG considered these recommendations and funded the installation of a modified wave measurement system on board the CORT. This system is described below. The Raytheon marine radar was not installed due to lack of funding.

### Wave Measurement Device Test and Evaluation

During the fall of 1978, NRL instrumented the M/V STEWART J. CORT to perform a test and evaluation of the

wave measurement system consisting of the NRL microwave radar altimeter (previously used on the SSC SL-7 project), a Collins Radio Co. radar altimeter, four accelerometers (vertical and horizontal at microwave and on a roll-stabilized platform on the pilot house top), and a Digital Equipment Corporation PDP-11/03, mini-computer based, data acquisition system. Figure 2 shows the data acquisition system in the pilothouse of the CORT. Data was recorded on floppy disks during the test and evaluation of the wave measurement system. With this system, point spectra, rather than directional spectra, were obtained. Figures 3-7 show the layout of the wave measurement system.

The Collins Radio Company, ALT-50 Radio Altimeter System, including the 860F-2 Radio Altimeter, was designed to provide altitude information for general aviation aircraft. The Collins radar transmits a frequency modulated continuous wave signal to the sea surface and receives the reflected signal. It processes the received signal to produce a dc analog signal proportional to the range from the antennas to the sea surface. The Collins radar uses a linear modulation of its transmitted frequency to obtain range resolution. Figure 8 shows the sawtooth shaped modulation wave form. Figure 8 also shows, that the return wave form is shifted in time due to the round trip time of flight of the signal. The instantaneous frequency difference between the transmitted and received signal is used as a measure of the range from antenna to sea surface.

The NRL microwave radar achieves its range resolution with a two nanosecond pulse. The time for the pulse to travel from the antenna to the sea surface and back is measured 800 times a second and then eight are averaged to give ten range values per second. The range tracker circuit updates pulse to pulse the programable time delay that is a feature of the scope. The range tracker senses changes in return pulse time position and adjusts the time delay to keep the pulse centered in the range window. This time delay represents the time from the transmission of a pulse to its return. Knowing the speed of light (i.e. the speed of the radar pulse) allows the calculation of the range from the antenna to the sea surface. Figure 9 shows a block diagram of the operation of the NRL microwave radar.

Verification of on-board measurements with NOAA wave buoy data (Copper Harbor, Michigan) and with a hindcast

analysis by the Army Corps of Engineers both proved to be ineffective. Validation was attempted by comparing radar wave measurements with those of a NOAA wave buoy positioned in Lake Superior 2 miles off Copper Harbor, Michigan. This effort proved to be unsuccessful due to (1) infrequency of rendezvous with the buoy, (2) distance of CPA with buoy (varied from 2 to 10 miles) and (3) the difference in water depth, wind speed and fetch between the buoy and the CORT. (Reference 11) evaluates the data obtained by comparing spectral analyses of both radars with visual observations and with a few NOAA buoy measurements. Generally, the comparisons show some agreement but the evidence was not conclusive.

During the fall of 1978, a particularly interesting set of data was collected on 10 November while the CORT was at anchor off Superior, Wisconsin. Winds were 30 knots from the northeast; observed wave height was 8 feet. Figures 10 and 11 show the spectra for both the Collins and NRL microwave derived from a series of three minute runs taken at the times indicated. The peak at 0.17 Hz in the 2112 record is thought to be due to the effect of a passing vessel. The agreement shown between the Collins and the NRL is excellent. This indicates that the differences in the spectra taken with the vessel underway can be explained by the bow wave. This led to the longer boom used for the Collins antennas, starting in the 1979 season, to get them out ahead of the white water. Figures 4, 5 and 7 show the boom position and configuration.

#### Damping Coefficient Determination

One illusive parameter in the study of springing had been system damping. It has still not been completely resolved. System damping is a combination of the hydrodynamic, structural, cargo, and out of phase seaway damping. To determine the damping for Great Lake ore carriers, stress recordings from strain gauges mounted on three ore carriers were analyzed. The three vessels used were the M/V STEWART J. CORT, M/V ROGER BLOUGH and S/S EDWARD L. RYERSON.

In June 1977, Teledyne was contracted by the USCG to transfer specified analog stress records from these three vessels to FM magnetic tape. These stress records contained intervals representing high, medium, and low

stress levels during loaded and ballasted conditions. These magnetic tapes were provided to Structural Dynamic Research Corporation (SDRC), under separate USCG contract, to determine the system damping coefficient for each specified interval of the stress records.

The method of analysis utilized by SDRC is known as MODAMS (MODal Analysis and Modeling System). It uses a multi-degree-of-freedom curve fit to the frequency response data over a specific frequency range. The algorithm used by SDRC is explained in Reference 12. To determine a "feel" for the approximate magnitude of the damping values determined by SDRC for the three vessels, a mechanical method which utilizes the decay period of filtered records from existing stress records was used to determine the different springing parameters. Once the peak springing stress is reached on a specific interval, the analysis measures the rate of decay of the oscillations as they decrease in amplitude.

Table 3 is a comparison of the SDRC results with the mechanical method. The differences in the calculated damping factors appear dramatic. But the fact that only analog stress records (digitized by Teledyne) during periods of vessel springing were available and from these SDRC developed a list of damping factors and associated frequencies at springing which matched "fairly" well with a mechanical analysis from apparently disassociated springing records. From this point of view the results from SDRC were very encouraging despite the differences shown in Table 3.

The unknowns in both analyses are (1) the components of the total damping, (2) the method and distribution of seaway loading on the vessel, (3) the out-of-phase/in-phase characteristics of the seaway with the hull response, (4) understanding of the full complexity of the hull structure, and (5) more accurate and complete description of the sea conditions (i.e. wave height, wave length, wave direction, wind parameters, and actual loading conditions).

#### Full Scale Pressure Distribution Measurements

In 1978, the SSC contracted with DTNSRDC to collect pressure distribution measurements concurrently with the wave and stress measurements on-board the CORT. Fifteen

inserts and threaded through-hull fittings were installed in the hull of the CORT during her five-year drydock period at Bay Shipbuilding in Sturgeon Bay, Wisconsin, during August 1978. The location of the inserts were agreed on by the USCG and the American Bureau of Shipping. Pressure transducers (25 psig, later replaced with 50 psig due to ice damage) were installed in the threaded fittings. The locations chosen for the pressure gauges by ABS are shown in Figures 3, 5 and 12.

These measurements were taken because the current technology for predicting hydrodynamic pressures was not completely satisfactory. In the SSC project (SSC-1236) the hydrodynamic pressures computed by SHIPMOTION program could not be used directly by the DAISY FEM program. DAISY was then used in an attempt to correlate full scale measured stress data with various analytical analyses. The greatest potential for these measurements would be in a better understanding of springing.

The data collected on board the CORT during the fall of 1979 was given to the American Bureau of Shipping for analysis. In February of 1981, ABS discussed the results from the ABS pressure data analysis.

Figures 13 and 14 are samples of the results presented by ABS that were representative of the wave spectra and the pressure RAOs calculated by ABS. These two figures are only for one condition at one transducer (i.e. Condition 4, transducer #7). The comparison between the wave spectrum and the pressure spectrum look good (Figure 13). The comparison between the theoretical and experimental data (Figure 14) shows the same general trend above 0.8 Hz (wave frequency) but do not compare below 0.8 Hz. This was probably due to the lack of any significant low frequency content in the wave spectra.

Additional pressure measurements in 1981 were also considered to obtain data for oblique seas (zero speed, full speed, loaded, ship-wave angles of 0, 45, 90 and 135 degrees). As a result of a thorough review of the records from 1979 however, the SSC decided not to fund pressure measurements in 1981. This was primarily due to the availability of adequate oblique seas measurements in the 1979 data. Further discussion on the pressure measurements will be the subject of a future SSC report.

#### M/V STEWART J. CORT - Full Instrumentation

In the spring of 1979, strain gauges were installed on the CORT by DTNSRDC. The locations of these gauges are shown in Figure 15. During fall of 1979, simultaneous measurements of wave heights, stresses, and pressures experienced by the vessel were taken while operating in the Great Lakes. The amount of data to be collected required the addition of a digital tape drive to the data acquisition system in the pilot house. Prior to each data collection period, a header log was recorded on the magnetic tape to label the data set.

The results of this data collection project provide stress and wave data measured simultaneously that can be used by researchers to investigate the phenomenon of springing and wave-induced responses. With the on-board data acquisition and reduction system on the CORT, some of the questions related to these phenomena were investigated on board ship. The wave spectra and the vessel response spectra associated with the acquired data from this project provided the USCG more information on the wave-induced and springing responses of the vessel and provided further understanding of the longitudinal strength needed by Great Lake ore carriers in excess of 750 feet in length.

The validation of the wave measurement system remained important as the full scale measurements continued. During the 1979 fall season, DTNSRDC attempted to validate the wave measurement system by deploying a wave buoy approximately 2 miles ahead of the vessel via USCG helicopters. Two modified Eastech Model 226 wave buoys were utilized. Due to unforeseen circumstances, only two buoy runs were obtained during the whole season. Reference 13 describes this project in more detail.

#### Wave Buoys

During the period of 1973 to 1975, John Dalzell of Davidson Laboratory, Stevens Institute of Technology, was contracted by the Ship Structure Committee (SSC) to reduce and analyze the wave meter data obtained on the Sea-Land McLean and to perform a comparison of the two wave measurement devices used on the vessel; specifically, the NRL microwave radar and a Tucker Meter. Mr. Dalzell concluded: "The evidence strongly suggests that neither of

the wave measuring systems can be regarded as a standard by which the other may be judged." (Reference 9, Vol 10) Due to this concern over verification of on-board radars for measuring sea states, a decision was made to obtain independent wave buoy information to validate the NRL microwave and Collins altimeters on board the CORT.

The wave buoys used were free floating accelerometer Wave Buoys (Model 226) built by Eastech Limited, Windsor, Nova Scotia. The self-righting buoy contains a transmitter, antenna, accelerometer unit and battery power supply. The buoy is made of fiberglass-reinforced plastic, pigmented blaze orange for visibility. All exposed metal parts are of corrosion resistant alloy. Figure 16 is a diagram showing the wave buoy and its basic components.

Teledyne Engineering Services (TES) had possession of the disassembled components for three buoys. TES was responsible for assembling the buoys, for laboratory tests of the buoys to insure proper operation, for modifications to the buoy for helicopter operations, for shipment of the buoys and for installation and check-out of the buoys on board the CORT.

The buoys provided an independent source of wave information for verifying the on-board measurements of waves. The buoys were deployed two to four miles ahead of the vessel by USCG helicopters operating out of either USCGAS Chicago, Illinois or Traverse City, Michigan.

The output voltage to acceleration sensitivity, provided by Teledyne Engineering Services was based on a static calibration carried by tilting the buoy to vary the vertical component of acceleration and recording angle and output voltage. Comparison of the buoy and the Collins wave measurement results for the 1979 season showed large discrepancies. This suggested that a dynamic calibration was required. Such a calibration was carried out by the USCG at the NOAA buoy calibration rotating arm facility at the Washington Navy Yard. The buoy is shown mounted in the arm in Figure 17. The resulting calibration was found to be the same linear function of frequency for both buoys and is shown in Figure 18.



The scenario utilized for buoy-helicopter operations was as follows:

(a) Buoy storage - Originally, each air station was prepared to store a buoy (with one spare at Chicago) at their facility and would transport the buoy to their rendezvous with the CORT. Considering the storage and handling problems of the buoy within the helicopter, it was decided to carry the buoys on the CORT.

(b) Buoy pick-up and return - Since the buoy was already on the CORT, the helicopter hovered over the vessel and received the buoy via the helicopter hoist hook attached to the helicopter (Figure 19). The buoy had a 10 foot web strap with floatation foam attached to its lifting pad eyes (Figure 16). The researchers on board the vessel handled the buoy with minimal involvement from the ships' crew.

(c) Buoy deployment - The wave buoy was suspended approximately 20 feet below the helicopter during flight. Once the buoy was lowered to the water, the helicopter crewman would release the hook and allow the buoy to float free. Occasionally, in 7-8 foot seas, the buoy was dropped 4-5 feet with no damage to the buoy.

(d) Data runs - The buoy usually remained in the water for 20-30 minutes. The helicopter would remain in the general vicinity of the vessel during this time. Strong signals from the buoy were received at 1-1/2 miles range ahead and continued to about 1-1/2 miles astern. Every effort was made to minimize the amount of ships' wake that the buoy encountered.

(e) Buoy retrieval - The sea conditions desirable for the data runs with the wave buoy would have involved 15-20 foot seas and 30-35 knot winds. Retrieval of the buoy was planned with these conditions in mind. However, due to extremely mild seasons in 1979 and 1980, the heaviest seas encountered with researchers on board were 8-9 feet and 35 knot winds. The approach used was as follows: the buoy had a lifting bridle attached to it for horizontal lift and transport (a 10 foot web strap with styrofoam floats was attached to

the bridle); the web strap was snagged with a grappling hook from the helicopter; the web strap was then secured to the helicopter hoist; a 45 minute smoke flare was occasionally deployed with the buoy to increase its visibility for retrieval.

(f) Number of data runs - Available on-scene time for the helicopters as approximately 1-1/2 hours. During this time it was usually possible to obtain two data runs before the helicopter had to return to shore for refueling.

(g) Area of operation - Several runs were made in southern and northern Lake Michigan and in Lake Superior. Figure 20 shows the areas of operation and the position of the NOAA wave buoys. Aviators from Traverse City carried out the operations in northern Lake Michigan and Lake Superior. Aviators from Chicago carried out those in southern Lake Michigan. Refueling of the helicopters was accomplished at five different locations, Hancock, Pellston, Marquette and Sault Ste Marie in Michigan and Milwaukee, Wisconsin (Figure 20). Operation in Lake Superior was preferable since sea conditions usually were optimal between Copper Harbor and Whitefish Bay due to the large fetch for winds coming from the northeast across Lake Superior.

During the 1979 season, only two helicopter-CORT rendezvous were accomplished but only one achieved usable results. During the first mission, a helicopter from Traverse City was on scene in Lake Superior when technical difficulties developed with the buoy receiver. The mission was aborted with no data obtained. The second mission in Lake Michigan resulted in two data runs being obtained. The reasons only two runs were obtained in 1979 were: (1) the DTNSRDC researchers waited for significant seas to develop, (2) when seas were best, the helicopters did not fly (due to weather, night, or distance), and (3) when helicopters were available, the high seas needed were not being experienced.

#### Collins, NRL Microwave and Buoy Comparison

Portions of the data collected on board the CORT during the buoy runs of 13 November 1979 were analyzed by the USCG to evaluate the NRL microwave data which was not examined by DTNSRDC.

Time histories of the Collins range, NRL range, and buoy acceleration are shown in Figures 21, 22 and 23, respectively. To compute the Collins and Buoy spectra, the first 13 minutes of each record were analyzed using every other point ( $N=4096$ ,  $dt=.2$  seconds). The data were Fast Fourier Transformed, and twenty frequency components averaged to yield 40 degrees of freedom. The buoy acceleration spectrum was then transformed from a displacement spectrum by dividing by  $w^4$ . It was converted then to an encounter spectrum using the experimentally derived calibration curve (see Figure 16 for calibration curve), the actual ship speed, relative heading and the appropriate Jacobian.

Because the NRL microwave went into the "hold mode" frequently, (as shown in Figure 22 by the spikes of 4096 due to the setting of the "warning bit" in the signal), the data was analyzed by taking six 100 sec (512 point) segments starting at times 100, 450, 550, 920, 1040, and 1350 seconds. By averaging three frequency components for each of the six segments and then combining the six, 36 degrees of freedom were obtained.

The buoy spectra are shown in Figure 24. The large values at low frequency are due to the magnification of noise and should be ignored. The existence of two distinct peaks is immediately apparent. This is indicative of two separate wave systems. The transformation to encounter frequency was made assuming all waves were from  $0^\circ$  ship-wave relative angle. With the existence of two wave systems, it is possible that one was from other than  $0^\circ$  relative and has thus not been transformed properly.

The Collins and NRL spectra are shown in Figure 25. The agreement shown is excellent. The double peaks are obvious in both curves.

Figure 26 shows all four spectra together. The comparison between the buoy and ship board measurements shows that, as was suspected, the two wave systems are from different directions. The larger peak of the predominant wave system has been transformed properly, but the secondary system was not from  $0^\circ$  and has thus been shifted to too high a frequency.

The significant wave heights derived were:

	CG	DTNSRDC
Buoy	2.3	2.32
Collin	2.9	2.97
NRL	3.0	not analyzed

These show quite good agreement for these low wave heights.

During the 1980 fall operating season of the CORT, additional wave, buoy and stress data was collected from the vessel. The primary emphasis for this period was to complete the verification of the accuracy of the NRL microwave and Collins wave height altimeters by obtaining more wave buoy data. Table 4 shows the comparison of the significant wave height measured using the NRL microwave, the Collins and the buoy compared to the observed wave height. Figures 27 - 32 show the spectral plots. The important point here is to compare the respective spectra among themselves and not directly with the observed wave height. There is considerable error (human) involved in estimating wave height. The agreement shown between the Collins and the wave buoy was good, usually within + 1.0 feet for 5 to 7 foot seas. The comparison between the microwave and the buoy was good sometimes and very poor at other times. This is due to incomplete analysis of the NRL microwave data. Since when the complete analysis of the NRL microwave was carried out, the comparison with the Collins, and buoy was good, the extra analysis effort required was not expended for all runs.

#### 1979 RAO Comparisons (measured vs. theoretical)

During the preliminary data analysis by DTNSRDC in 1980, RAO's (response amplitude operators) were developed from the stress and wave measurements. These were then compared with theoretical RAO's computed by American Bureau of Shipping (ABS), Webb Institute of Naval Architecture, the University of Michigan (UM) and Det norske Veritas (DnV). Table 5 lists the conditions chosen for the RAO comparisons.

Specific information provided to each organization was:

- (a) Loading Manual
- (b) Still water shear and bending moment curve

- (c) exact location of pressure gauges
- (d) vertical center of gravity: 25.53' above baseline
- (e) frequency range for RAO's: 0 - 0.5 Hz.
- (f) requested bending moment RAO's  
be calculated from .2 - 2.5 rad/sec with increments of  
0.05 rad/sec

Figure 33 is a sample comparative plot for one condition. Specific comparisons between the measured and theoretical predictions with more discussion may be found in Reference 9.

#### 1980 RAO Comparisons (Maindeck vs Bottom)

As shown in Figures 3 and 13, the CORT was instrumented with maindeck and bottom strain gauges. Figure 34 shows a typical bottom strain gauge time history. While on board, a damaged gauge on the starboard maindeck was discovered. These gauges have a diadic configuration and one gauge on the starboard arm (which has two gauges) of the strain gauge bridge was found damaged. Each gauge was rated 120 ohms. Since these are welded gauges and are covered with an angle iron making them inaccessible, a 120 ohm fixed resistance was wired into the bridge for purposes of continuing the 1980 measurements. Thus during the 1980 season, the main deck gauge was not in the standard configuration.

RAO's for runs 3, 4, and 7 and for runs 34, 35, and 36 are shown in Figures 35 - 38. These RAO's were developed using only the Collins wave spectra. The bottom stress RAO's (Figures 36 and 38) show better consistency than the maindeck RAO's (Figures 35 and 37). The ordinate dimensions are PSI per foot of wave height.

#### Data Analysis

Additional full scale measurements on the CORT were performed in the fall of 1980 and are scheduled for the fall of 1981. Before the 1981 measurement begins, a thorough data evaluation analysis is being performed to insure an improved measurement program for 1981.

The purpose of this step is to determine the confidence bands for the 1979/80 measured RAO's considering the

changes in the parameters (ie. speed, heading, wave height) and to review the results obtained by DTNSRDC's RAO comparison. Items considered include:

- (a) the self-consistency of the RAO's
- (b) the degrees of freedom with respect to the spectral resolution
- (c) the statistical variability of the estimates
- (d) the comparison of the estimates with theory

An RAO will be considered consistent if (1) all results obtained under comparable conditions of speed and heading fall within a 90 or 95% confidence band assuming that the process was random, stationary and a linear function of the encountered wave and 2) the coherence between the encountered wave and stress is reasonably high (i.e. in excess of 70%).

If the RAO's are found not to be consistent, then the data will be processed using the following nonlinear analysis procedures.

- (a) Maximum likelihood spectral analysis (or maximum entropy)

This analysis will be used to detect sharp spikes buried in noise, since springing usually is a very narrow band process and bias in spectral estimates is to be expected. This method is essentially a mechanized pre-whitening process which requires inversion of a relatively large matrix.

- (b) Pre-whitening Transformation

Since the wave spectral density at the springing frequency may be quite small relative to the peak density, a pre-whitening transformation for the wave spectrum will be used to provide additional information concerning the data.

- (c) Cross-bi-spectral analysis

This analysis will be employed to determine if quadratic nonlinearities are present.

During 1980, the Office of Merchant Marine Safety, USCG, initiated a project entitled "Numerical Simulation of Combined, Springing and Wave Induced Stress Response" to generate wave-induced and springing stress time histories from combined stress spectra obtained in 1979. This research was aimed towards developing and testing probabilistic models for the combination of wave-induced and springing stresses and towards the development of a basic simulation method.

As a continuation for the verification of the time history simulation, additional full scale data runs from 1979 and 1980 will be selected to:

- (a) Compute combined midship stress spectra
- (b) Develop time histories of the combined, wave-induced and springing stresses via the simulation and compare these with simulated time histories
- (c) Compute maximum stresses (combined, wave-induced and springing)
- (d) Determine combined stress maxima and their associated statistical tests
- (e) Check for consistency of the observed distribution with the analytical distribution of the short term maxima
- (f) Check the distribution of the maxima for the springing and wave induced stresses and establish their level of statistical independence

Following the 1981 season, a final and very thorough analysis project is scheduled. The analysis will combine all data records from 1979, 1980 and 1981 and will look at the "total picture" for determining the required longitudinal strength standard for the 1000' (or greater) Great Lakes ore carriers.

#### 1981 CORT Measurements

The 1981 measurements will be a continuation of the full scale measurements performed during 1978, 1979, and 1980 by Naval Research Laboratory (NRL), David Taylor Naval

Ship Research and Development Center (DTNSRDC) and the U. S. Coast Guard (USCG), respectively. The instrumentation used for the measurements from 1979 through 1980, Figure 3, will be used during 1981. The only exceptions will be the absence of the pressure gauges in the bow and the absence of wave buoy data.

Changes in the 1981 measurement program will include: replacement of all midship bending strain gauges, possible installation of duplicate gauges, continued wave measurements with the microwave and Collins radar altimeter and consideration of revamping the NRL microwave radar to remove data error caused data drop-outs. Based on 1980 measurements and comparisons between the Collins, microwave and buoy, confidence has been gained in the on board wave measurement system. Below is further discussion on the major points:

(a) Strain gauges - Due to the 1979 and 80 difficulties with the gauges and the confusing results from the maindeck and bottom strain gauges, it was decided that all strain gauges would be replaced and that an additional set of strain gauges would be installed as spares since only one season of measurements remains. Also being considered is the possible value of recording long term drift and changes in stress of the strain gauges and the separate recording of port and starboard gauges. These suggestions will be considered as the project schedule for 1981 becomes more firm.

(b) Wave measuring Radars - Continue using both the NRL microwave and Collins radar. The agreement between Collins and wave buoy is usually within  $\pm 1.0$  ft. The microwave is sometimes further off due to drop-outs in the measured data when the microwave enters the search mode. An investment in the microwave radar system to improve its operational accuracy and to eliminate searches and data drop-outs is being considered. This also would make the microwave more adaptable to the ocean environment for future SSC slamming projects.

(c) Static gauge calibration - Static strain gauge measurements will be performed during an in-port period at the beginning of the season. This will provide a static calibration of the strain gauges.



(d) Wave buoys - The wave buoys will not be used during the 1981 measurements. This decision was reached after the USCG had completed the 1980 buoy analysis comparison with the Collins and the microwave.

The ultimate objective of this final measurement season is to complete the springing research on the CORT and to arrive at some specific conclusions concerning wave induced and springing stress combination on a 1000 foot Great Lakes ore carrier.

The tentative fall measurement schedule is:

October	1 round trip
November	4 round trip
December	1 round trip

#### Conclusions

The Great Lakes springing research program demonstrates significant cooperative effort between a number of organizations. The results to date have been impressive. Model test, theoretical, and full scale results are now being combined to greatly expand our understanding of springing. The full scale response operators, made possible by the successful development of a ship board wave measuring system, provide the the link to the "real world" which is essential.

#### Acknowledgements

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The program managers within the USCG are Bill Cleary and Paul Cojeen and their effort expended for this project is appreciated.

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Table 1

M/V STEWART J. CORT  
PRINCIPAL CHARACTERISTICS

Length Overall . . . . .	1000'-0"
Length Between Perpendiculars . . . . .	988'-6"
Length on Waterline . . . . .	998'-6"
Beam, Molded . . . . .	104'-7 1/2"
Depth at Side, Molded . . . . .	49'-0"
Camber (straight line) . . . . .	0"
Tumble Home . . . . .	0"
Deadrise . . . . .	0"
Bilge Radius . . . . .	15"
Maximum Draft, Summer, Great Lakes, MLD . . . . .	27'-10"
Displacement, Long Tons (@ SLL MLD) . . . . .	74,400
Light Ship Weight, Long Tons . . . . .	15,510
Deadweight, Total, Long Tons @ 27'-10 . . . . .	58,890
Brake Horsepower, Normal . . . . .	14,800
Shaft Horsepower, Normal . . . . .	14,000
Revolutions Per Minute At Normal Power . . . . .	900
Propeller Diameter . . . . .	18.0'
Number of Blades . . . . .	4
Gross Tonnage (est) . . . . .	33,000
Net Tonnage (est) . . . . .	30,000
Crew Accommodation . . . . .	33
Operating Ballast Drafts . . . . .	9'-0"f, 20'-6"a
Total Cubic, cubic feet . . . . .	1,647,705
Ballast Cap. Total (All Tanks Except FP), LT . . . . .	38,872

No crew, stores, fuel.

HULL FORM DATA

Displacement Length, (LBP) . . . . .	988'-6"
Beam Molded . . . . .	104'-7 1/2"
Design Draft, Molded . . . . .	25'-9"
Displacement, Molded, Fresh Water, Long Tons . . . . .	68,330
Length - Beam Ratio . . . . .	9.45
Beam - Draft Ratio . . . . .	4.06
Length of Entrance, Feet . . . . .	160.0'
Length of Parallel Middlebody, Feet . . . . .	736.0'
Length of Run, Feet . . . . .	92.5'
Run - Entrance Ratio . . . . .	0.578
Block Coefficient (LBP). . . . .	0.924
Prismatic Coefficient (LBP). . . . .	0.924
Midship Coefficient (LBP). . . . .	0.999
Water Plane Coefficient (LBP). . . . .	0.975
Displacement - Length Ratio $/(LBP/100)^3$ . . . . .	70.74
Longitudinal Center of Buoyancy, Feet Forward Midships (LBP) . . . . .	4.45
Wetted Surface, Square Feet . . . . .	150,462
Designed Sea Speed, Miles per hour @ 25'-9" . . . . .	16.00
Designed Sea Speed, Knots (VK) . . . . .	13.89
Speed - Length Ratio VK/ (LBP)**.5 . . . . .	0.442

Table 2

1973 Midship Transducers

Storm	Date	Max Comb. stress	Max Springing stress	Max Wave induced stress
1	5/2	29,400	16,600	16,000
2	11/8	17,677 23,600	7,225 5,200	14,800 22,400
3	12/10	17,300 19,100	6,600 7,600	15,500 13,330
4	12/13	19,200	10,660	12,700

Table 3

Comparison of SDRC Damping Factor Results with Mechanical Results

	SDRC		Mechanical		$\frac{\text{SDRC avg} \times 100}{\text{Mech avg}}$
	Range	Avg.	Range	Avg.	
CORT	.00611-.0246	.014	.017-.048	.029	40%
BLOUGH	.0103-.0248	.01916	.020-.0304	.0251	76%
RYERSON	.00337-.00745	.00480	.024-.0289	.0265	18%

Table 4

Run #	Obs	Significant Wave Height		Buoy
		Collins	NPL microwave	
3	7	4.91	5.42	5.96
4	7	5.36	6.14	6.28
7	2	3.88	13.09	4.59
34	6	4.19	6.17	4.55
35	6	3.93	6.13	4.45
36	6	5.7	6.4	4.11



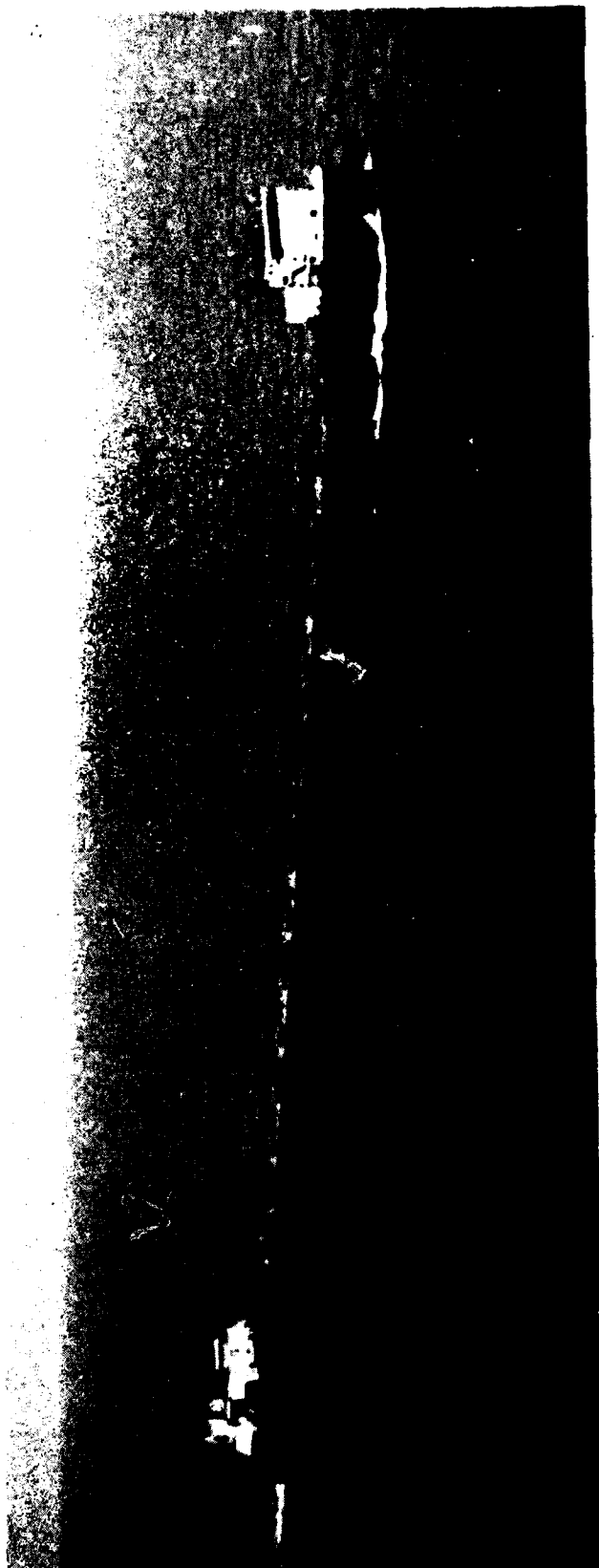
Table 5

<u>Condition</u>	<u>Speed</u>	<u>Draft</u>			<u>Ship Wave Angle (deg)</u>
		<u>FWD</u>	<u>MID</u>	<u>AFT</u>	
1	14.4	19'11"	20'7"	22'0"	6
2	14.4	19'11"	20'7"	22'0"	11
3	14.7	27'0"	27'0"	27'0"	6
4	14.2	27'0"	27'0"	27'0"	9
5	13.5	27'0"	27'0"	27'0"	23
6	13.5	27'0"	27'0"	27'0"	10
7	11.6	18'0"	19'11"	21'3"	0
8	11.6	19'11"	20'7"	22'0"	20

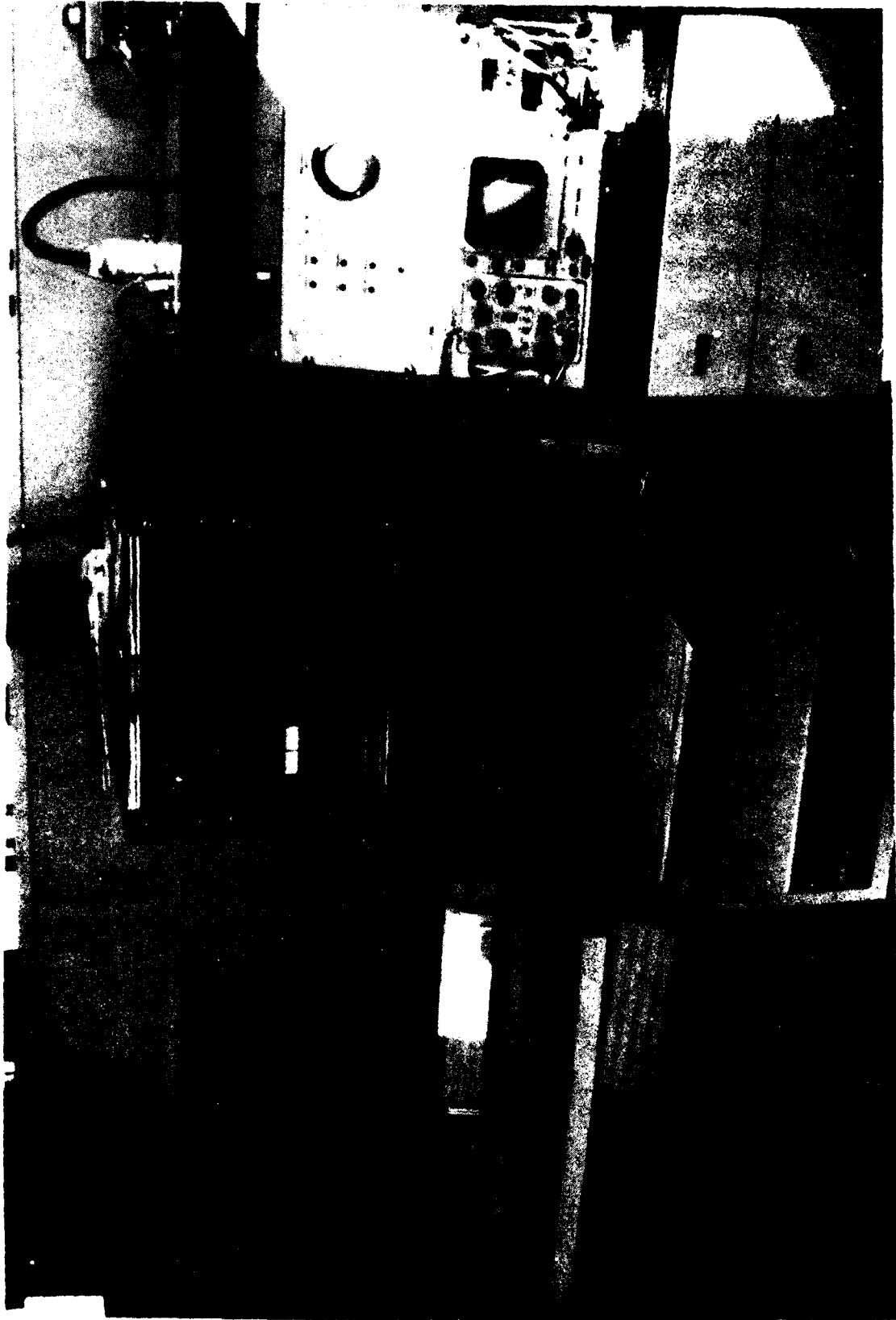
Figure

- 1 M/V STEWART J. CORT (PHOTO)
- 2 Data acquisition system in Pilot House (PHOTO)
- 3 Instrumentation of CORT
- 4 Bow view of instrumentation
- 5 Beam view of bow instrumentation
- 6 NRL microwave on Pilot House top (PHOTO)
- 7 Collins boom (PHOTO)
- 8 Collins radar modulation waveform
- 9 Diagram of NRL microwave radar system
- 10 Spectral plot from Collins radar
- 11 Spectral plot from NRL microwave radar
- 12 Location of pressure gauges - cross section
- 13 ABS wave spectra vs. pressure spectra
- 14 UM model pressure RAO vs. ABS pressure RAO
- 15 Location of midship strain gauges
- 16 Wave Buoy - Internal view & description
- 17 Wave Buoy on NOAA calibration apparatus
- 18 Wave Buoy calibration curve
- 19 Helicopter operations over M/V CORT (PHOTO)
- 20 Map of Great Lakes operations

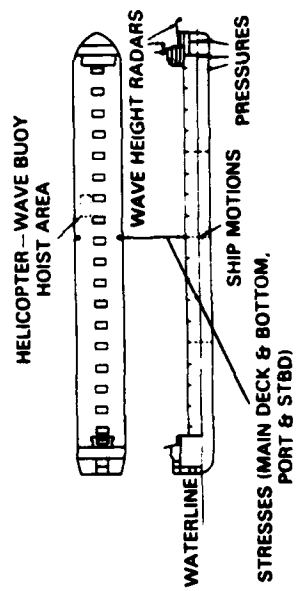
- 21 Collins time history plot (1979 Run #70)
- 22 NRL microwave time history plot (1979 Run #70)
- 23 Wave buoy time history plot (1979 Run #70)
- 24 Buoy - Encounter vs. Wave frequency
- 25 NRL microwave vs. Collins wave spectra
- 26 NRL microwave vs. Collins vs. buoy wave spectra
- 27 Wave spectra Collins, NRL microwave, buoy (1980 run #3)
- 28 Wave spectra Collins, NRL microwave, buoy (1980 run #4)
- 29 Wave spectra Collins, NRL microwave, buoy (1980 run #7)
- 30 Wave spectra Collins, NRL microwave, buoy (1980 run #34)
- 31 Wave spectra Collins, NRL microwave, buoy (1980 run #35)
- 32 Wave spectra Collins, NRL microwave, buoy (1980 run #36)
- 33 1979 RAO Comparison (theoretical vs measured)
- 34 Strain gauge time history plot
- 35 RAOs Maindeck/Collins (1980 runs 3,4,7)
- 36 RAOs Bottom/Collins (1980 runs 3,4,7)
- 37 RAOs Maindeck/Collins (1980 runs 34,35,36)
- 38 RAOs Bottom/Collins (1980 runs 34,35,36)

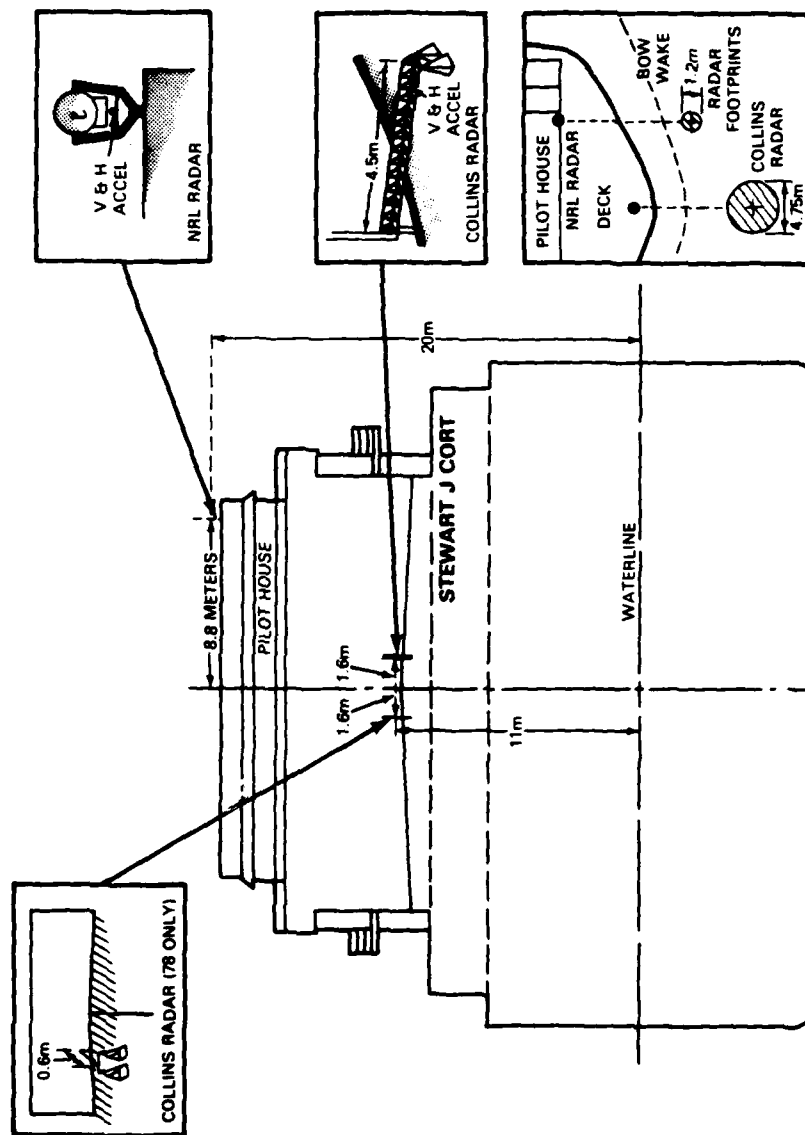


1 M/V STEWART J. CORT

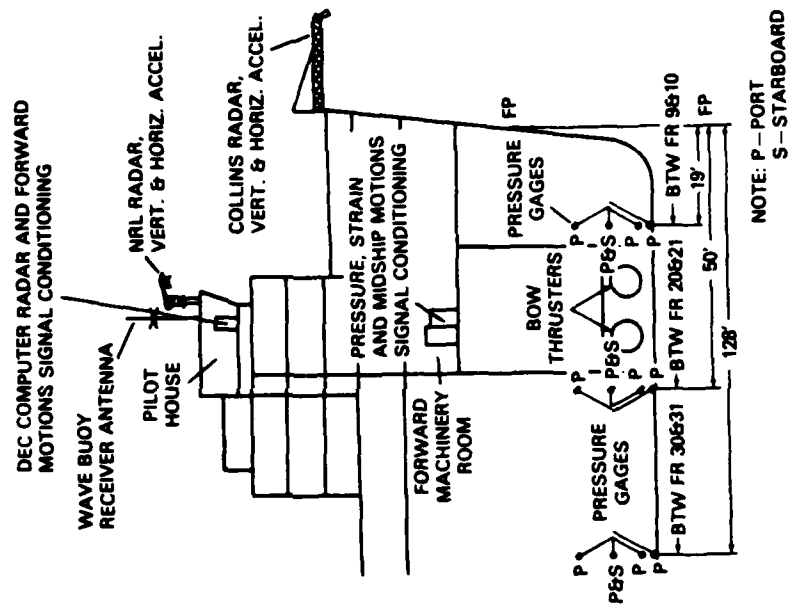


2 Data acquisition system in Pilot House



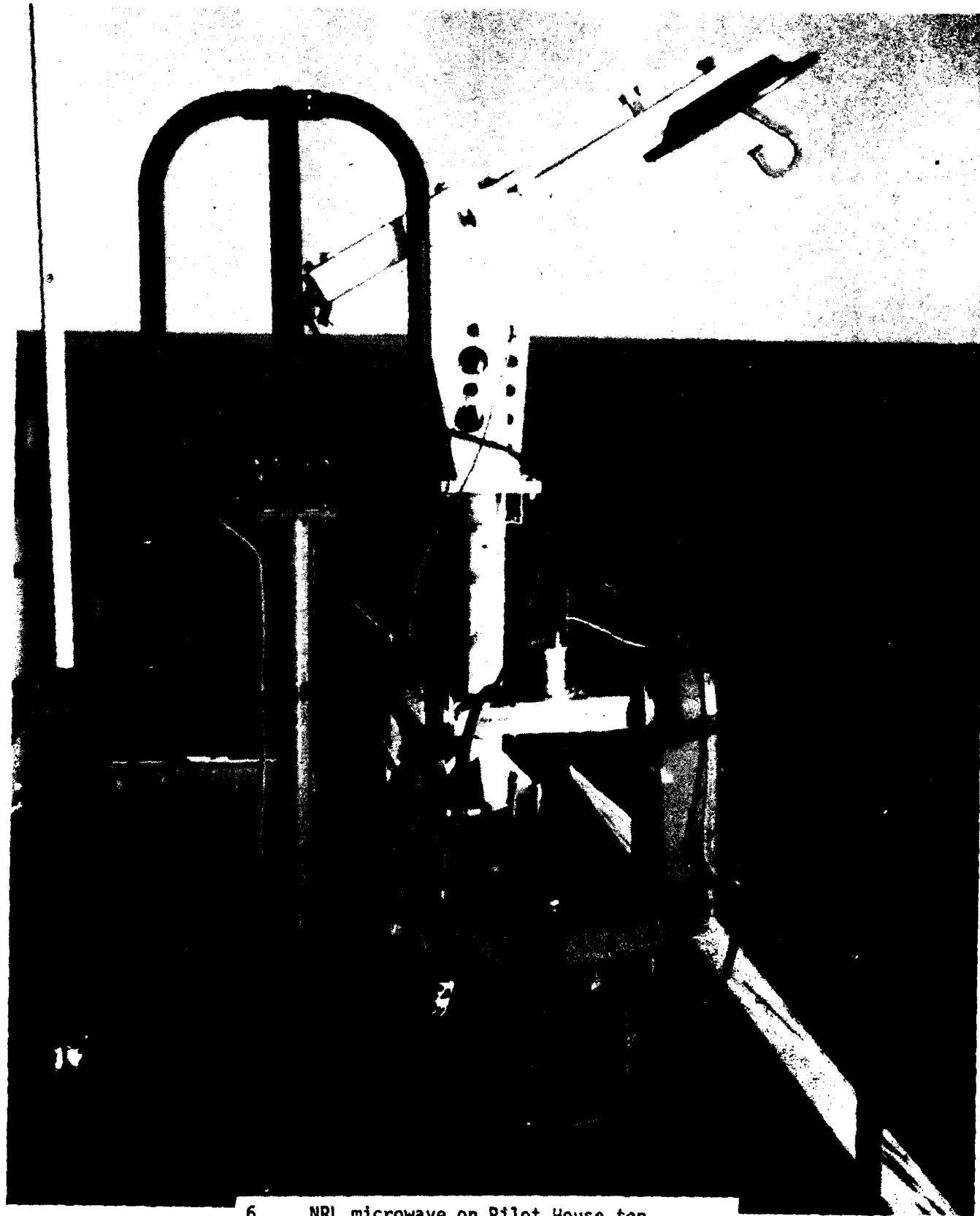


4 Bow view of instrumentation



5 Bear view of bow instrumentation

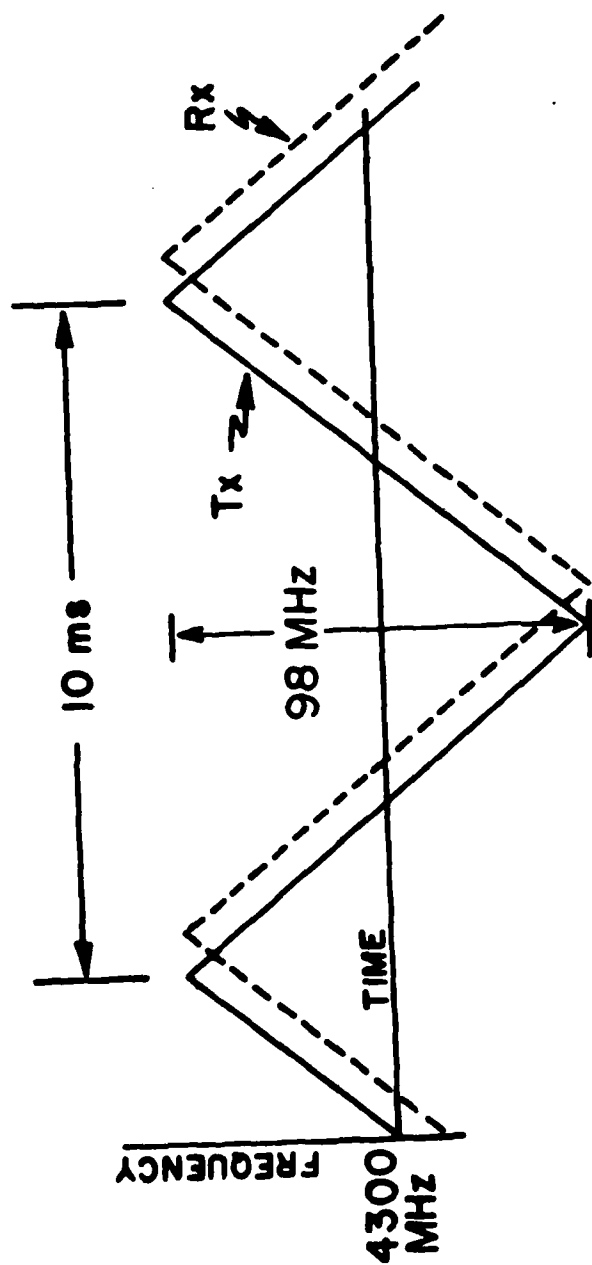




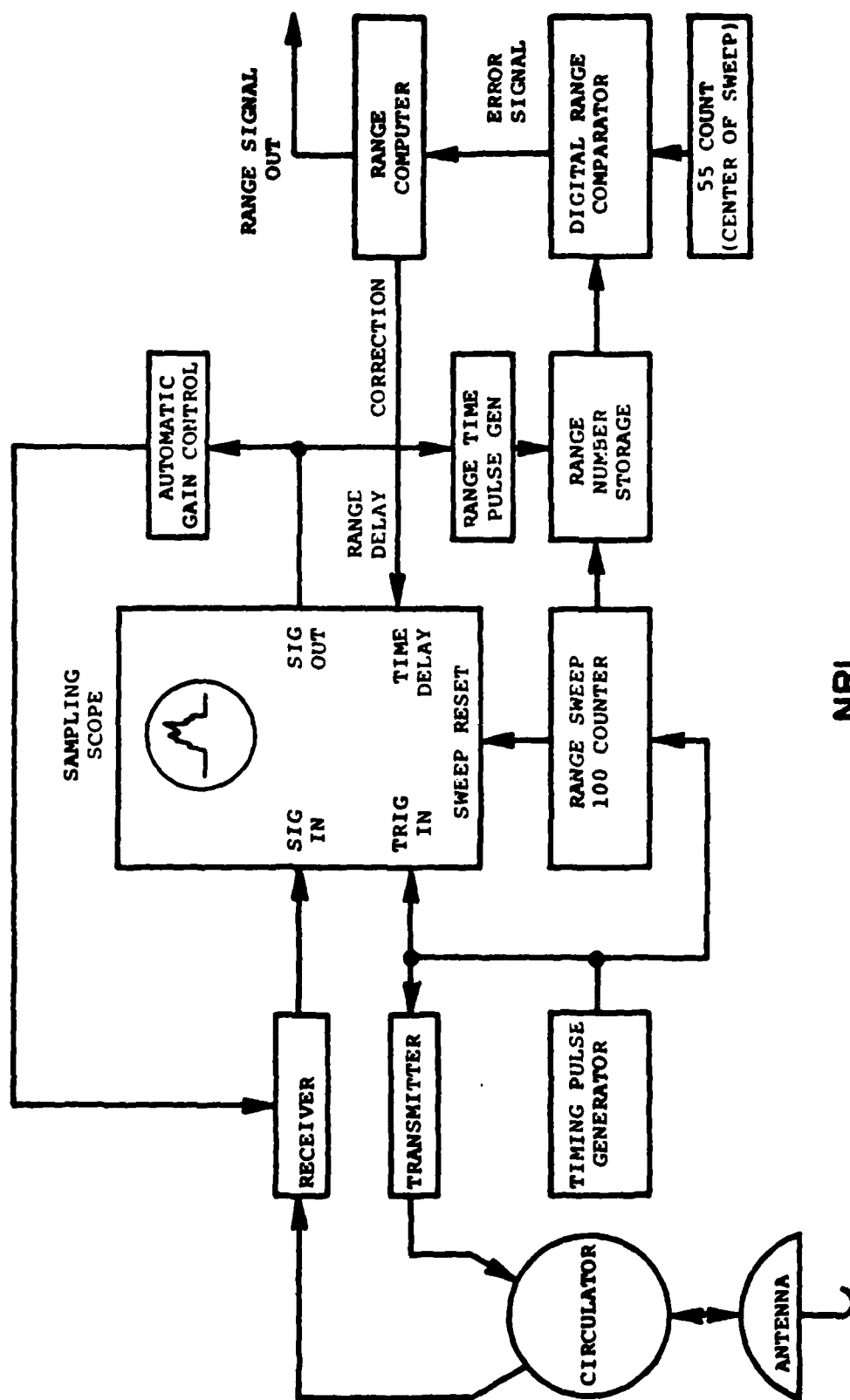
6 NRL microwave on Pilot House top



7 Collins boom

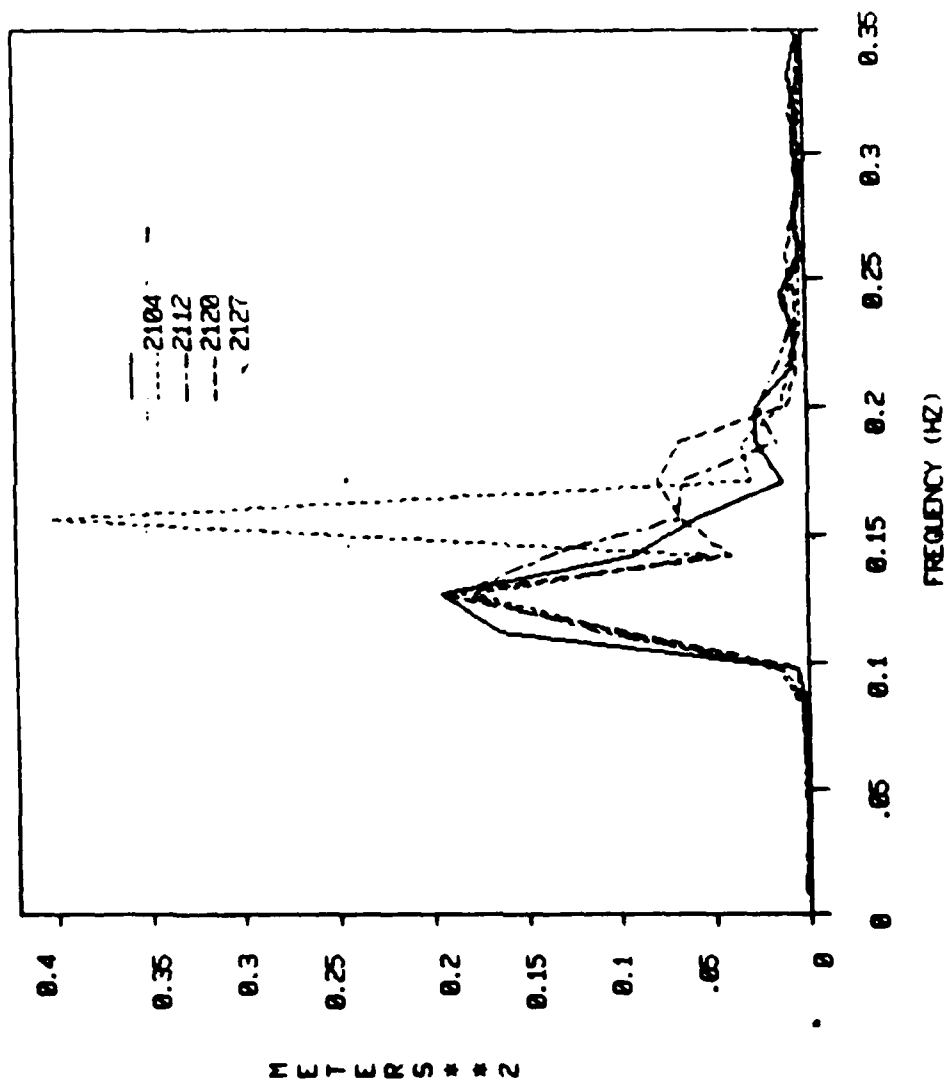


## COLLINS RADAR MODULATION WAVEFORM

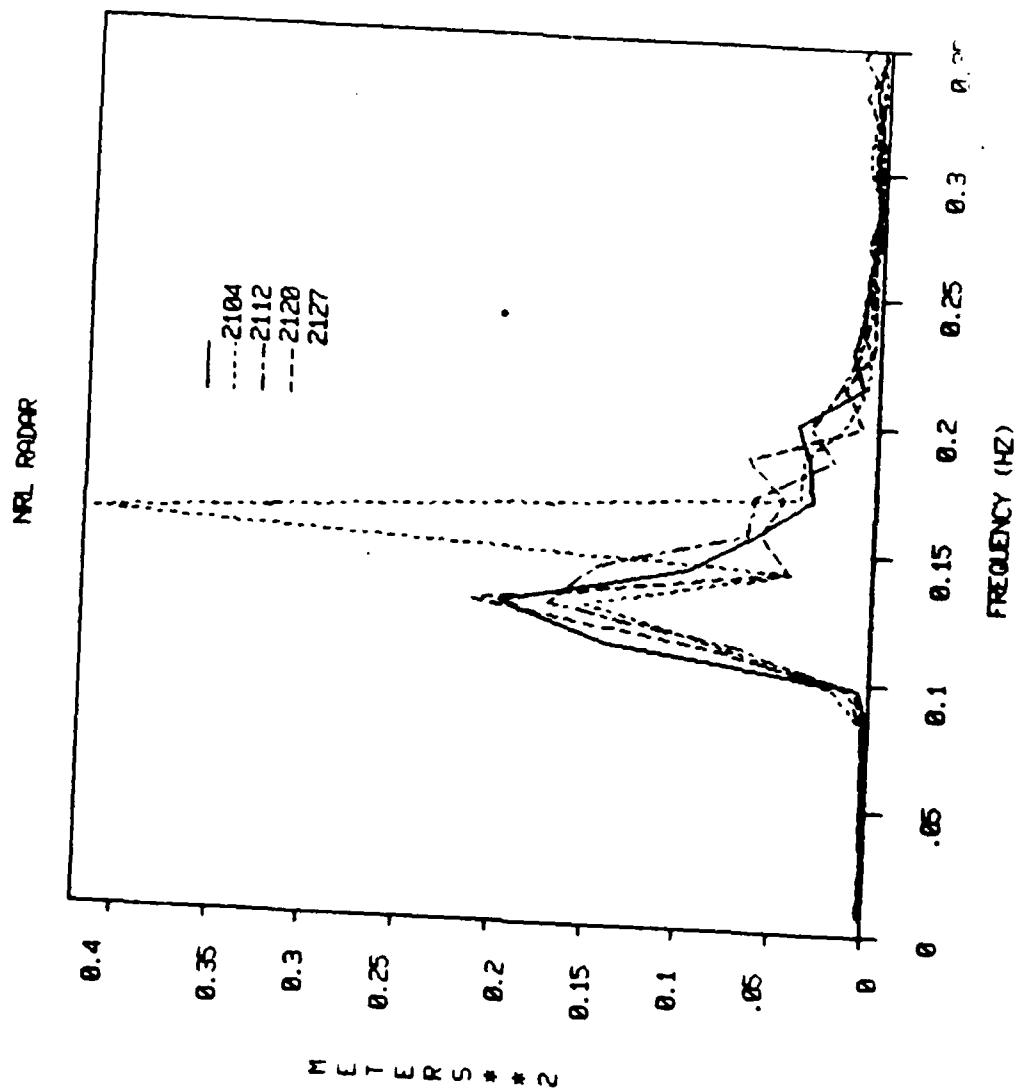


## NRL RADAR SYSTEM

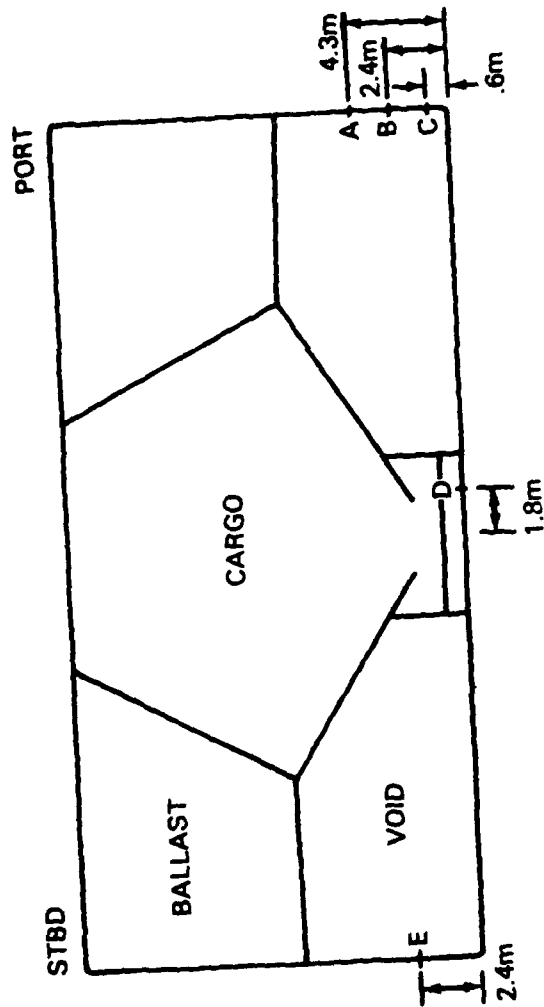
# COLLINS RADAR



10 Spectral plot from Collins radar

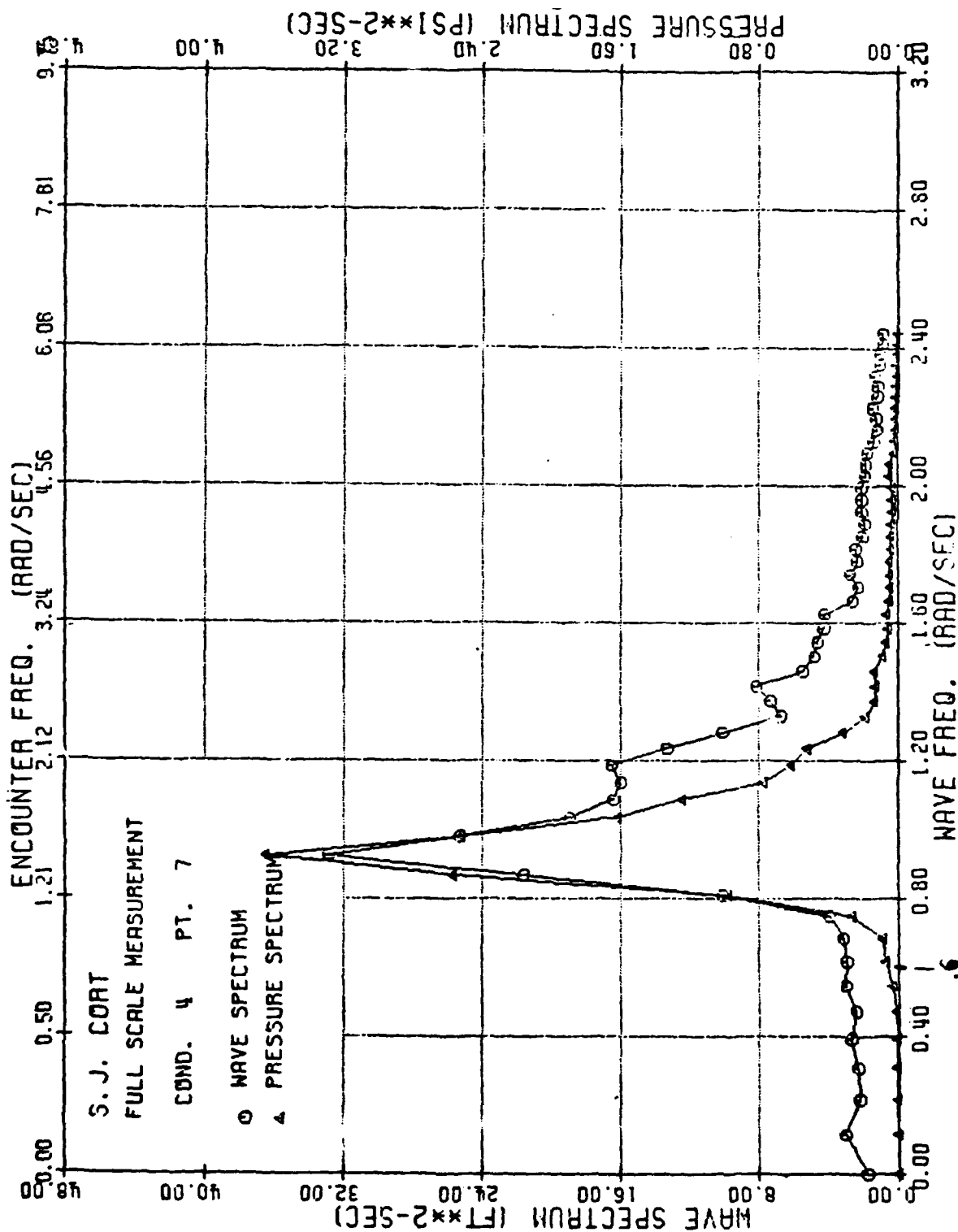


11 Spectral plot from NRL microwave radar

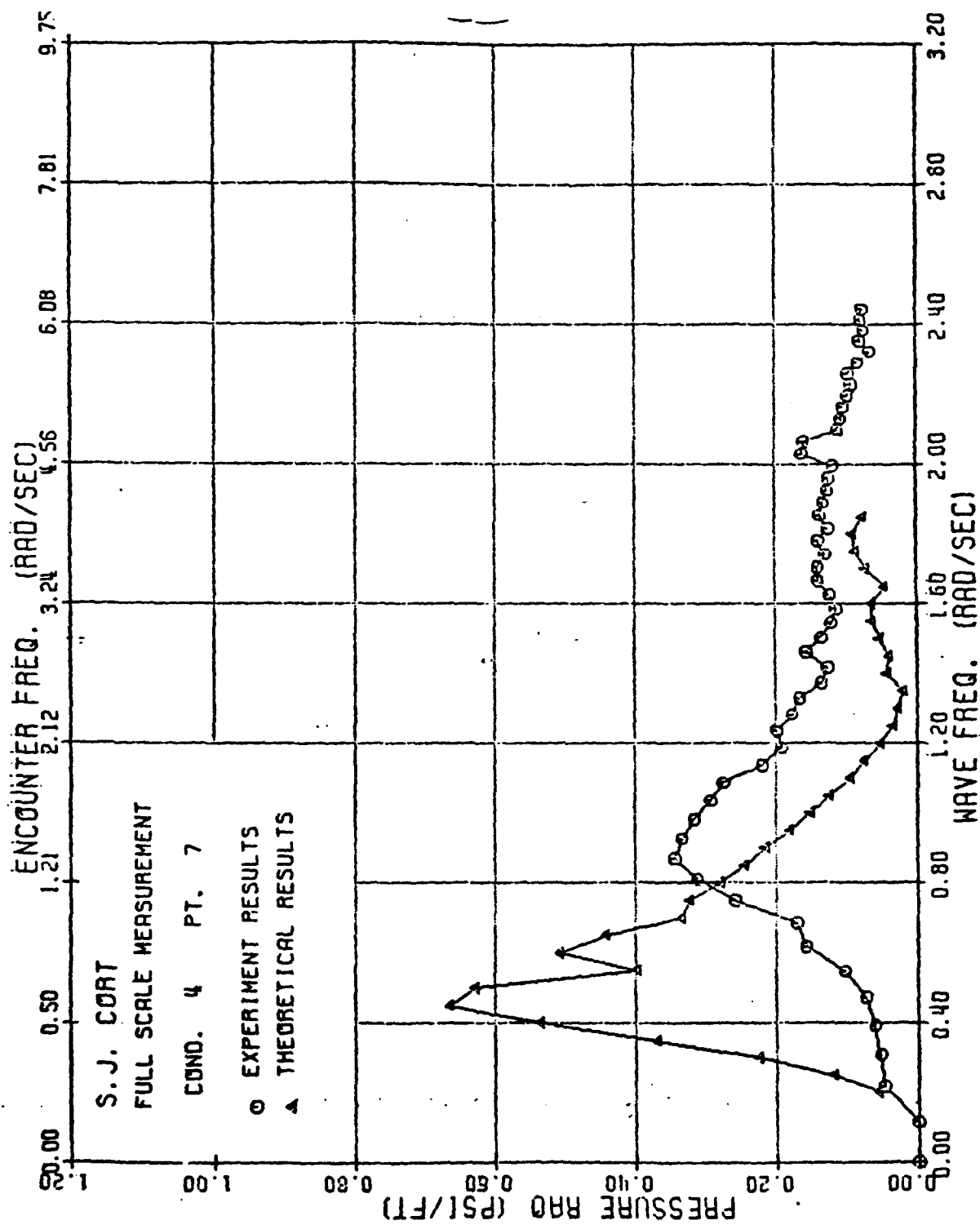


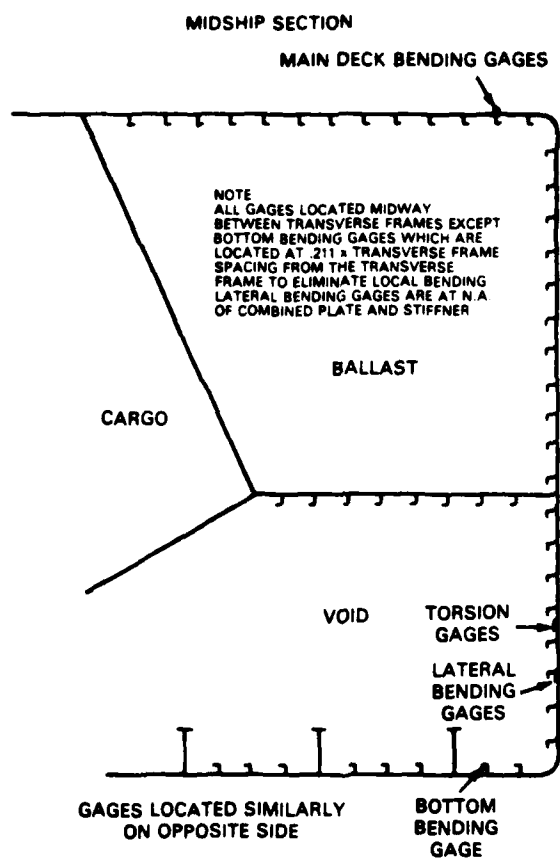
BETWEEN FRAMES 30 AND 31 LOOKING AFT  
SAME GAGE ARRANGEMENT BETWEEN FRAMES  
9 AND 10 AND FRAMES 20 AND 21

12 Location of pressure gauges - cross section

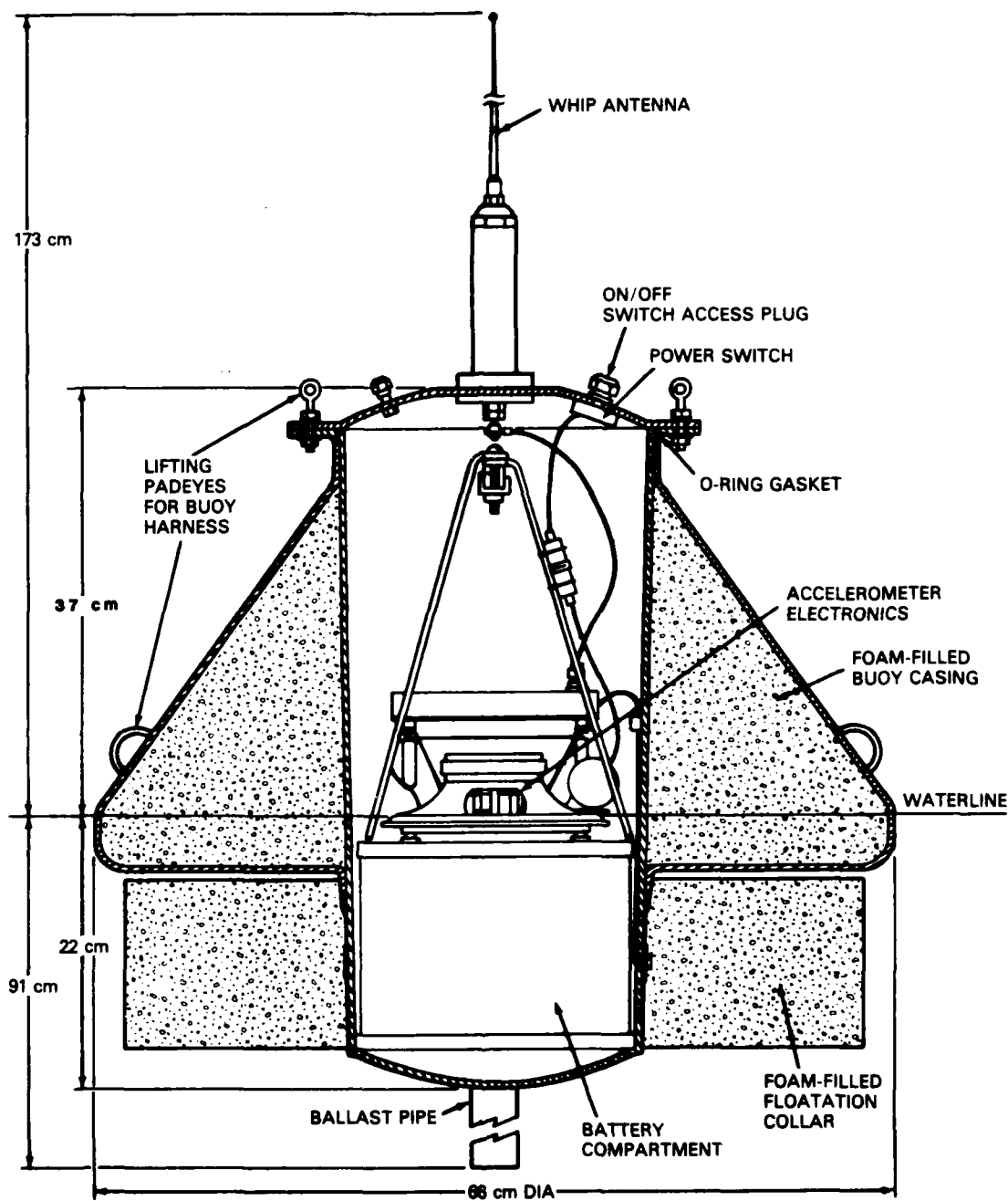




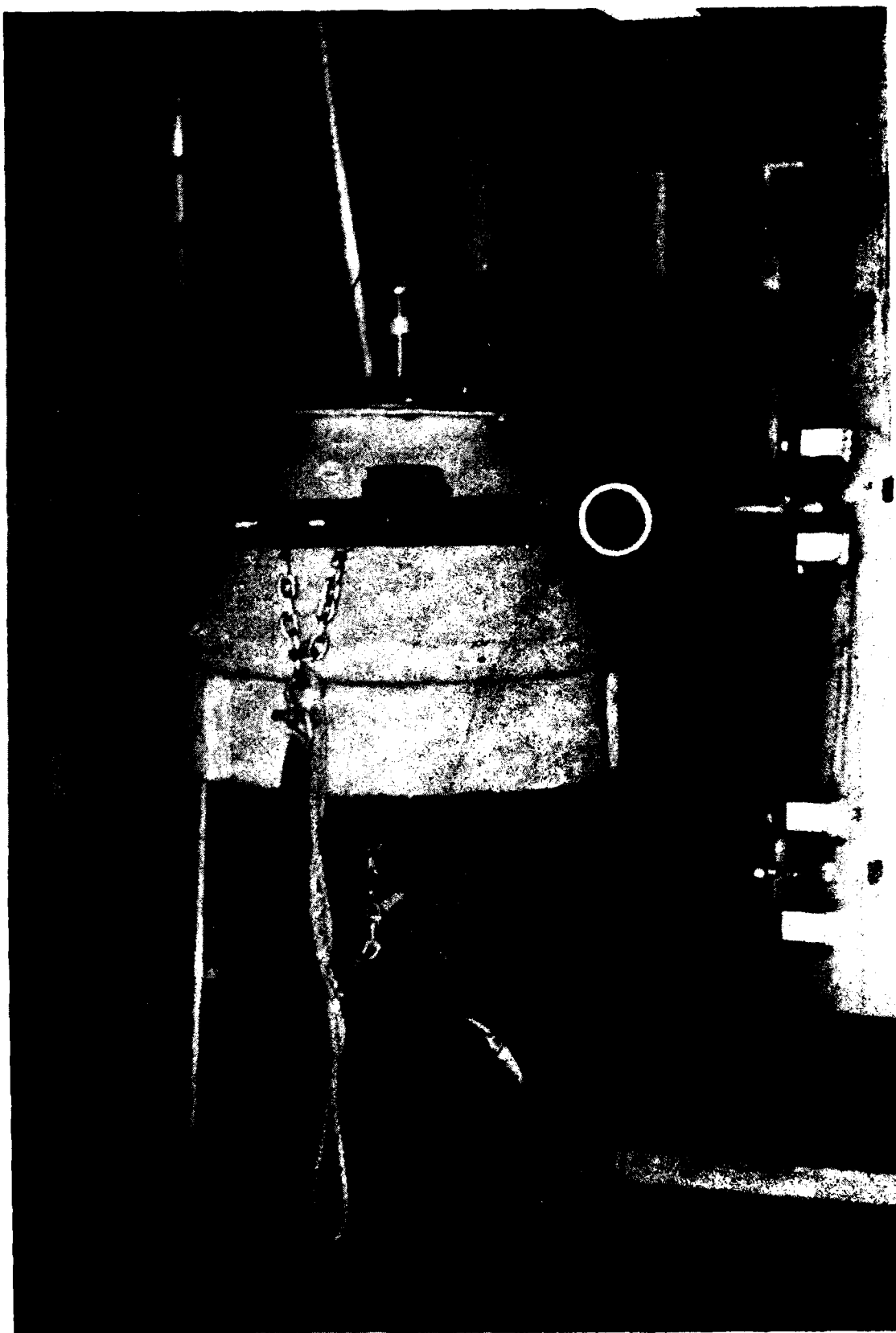




15 Location of midship strain gauges

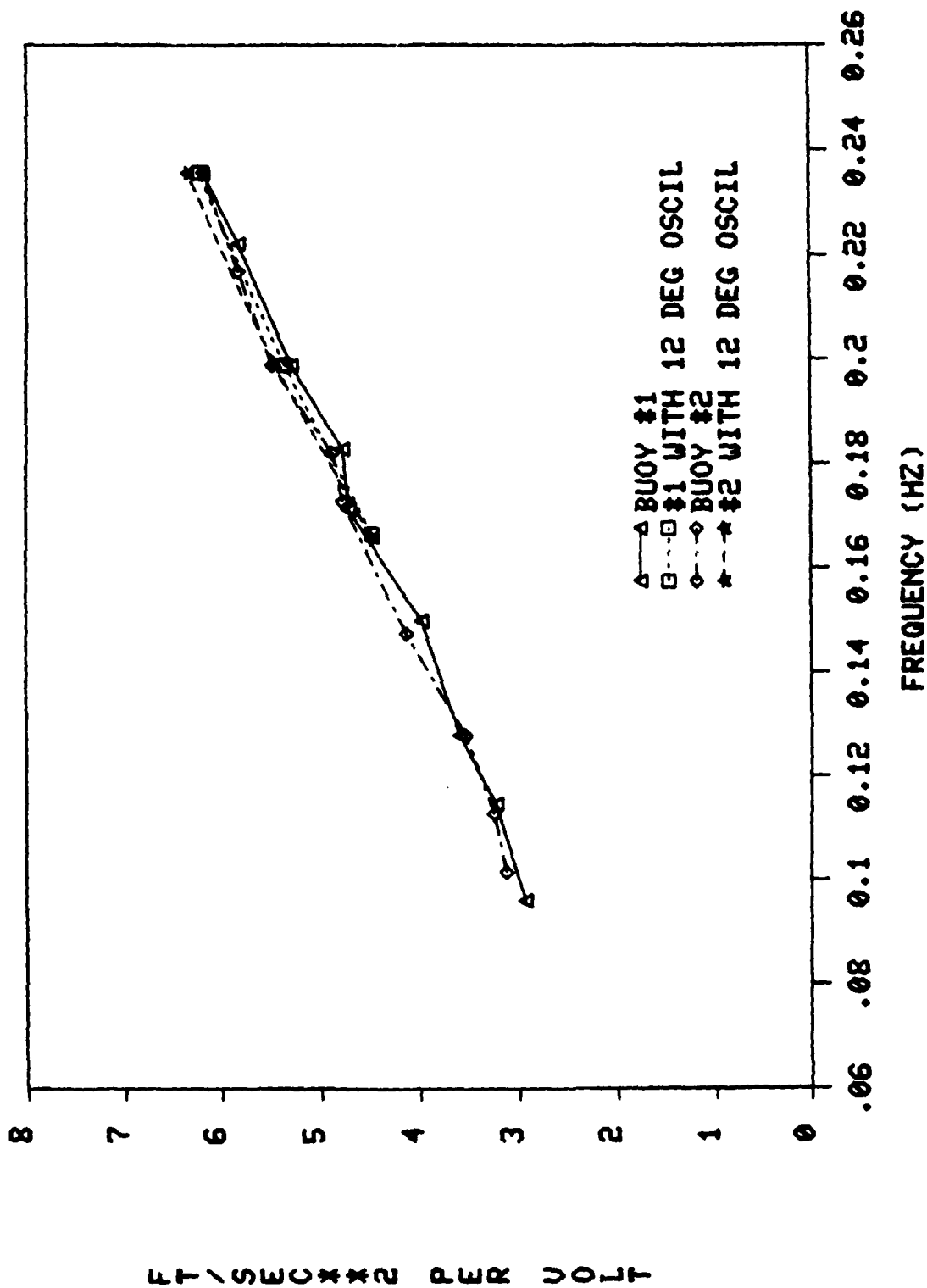


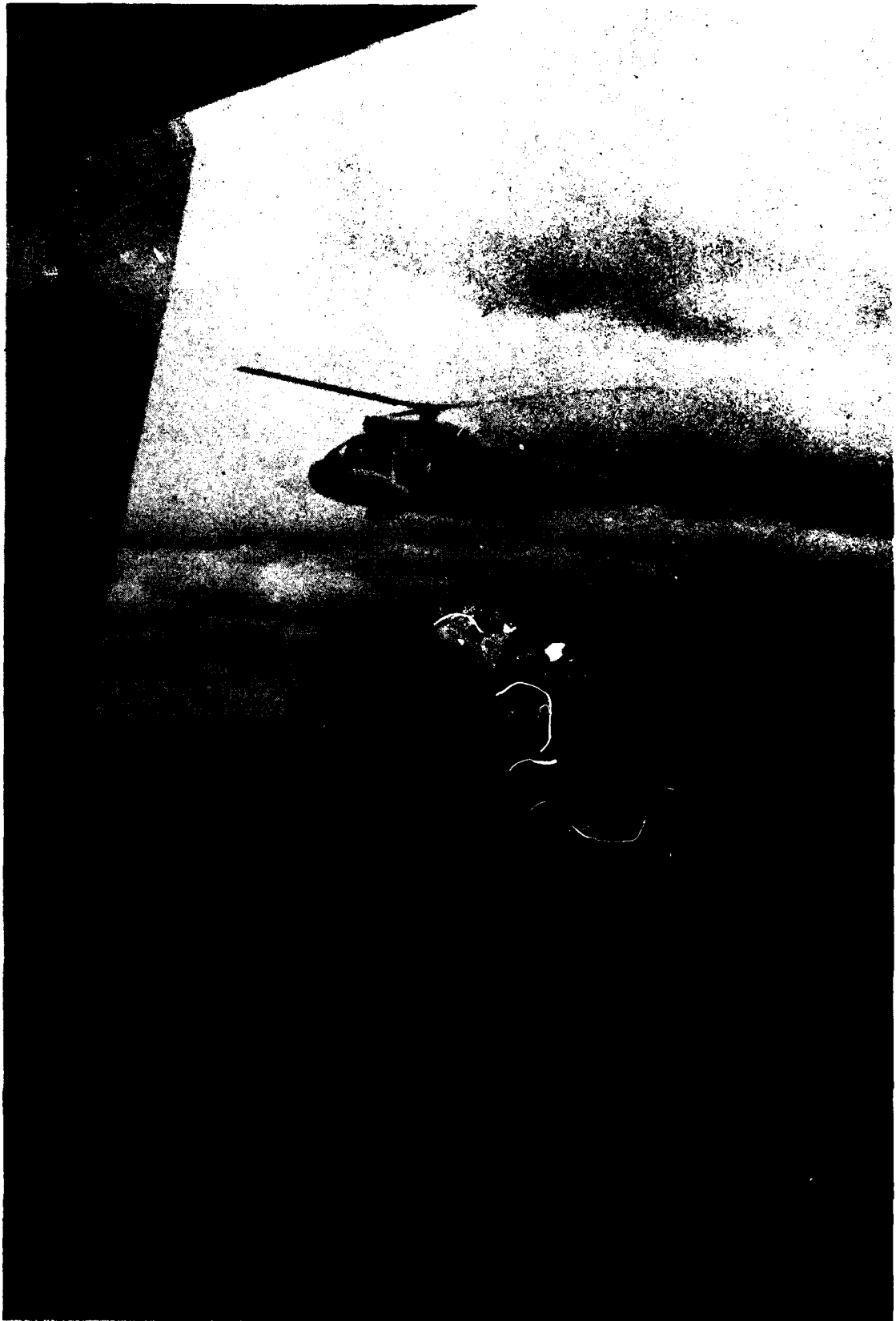
16 Wave Bouy - Internal view & description



17 Wave Buoy on NOAA calibration apparatus

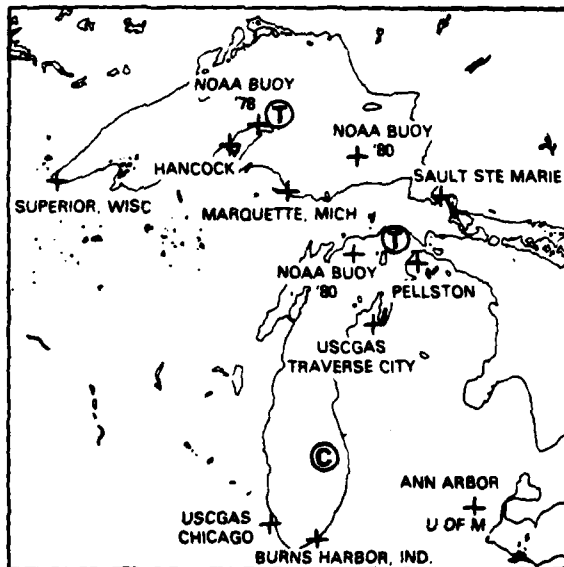
# BUOY CALIBRATION CURVE





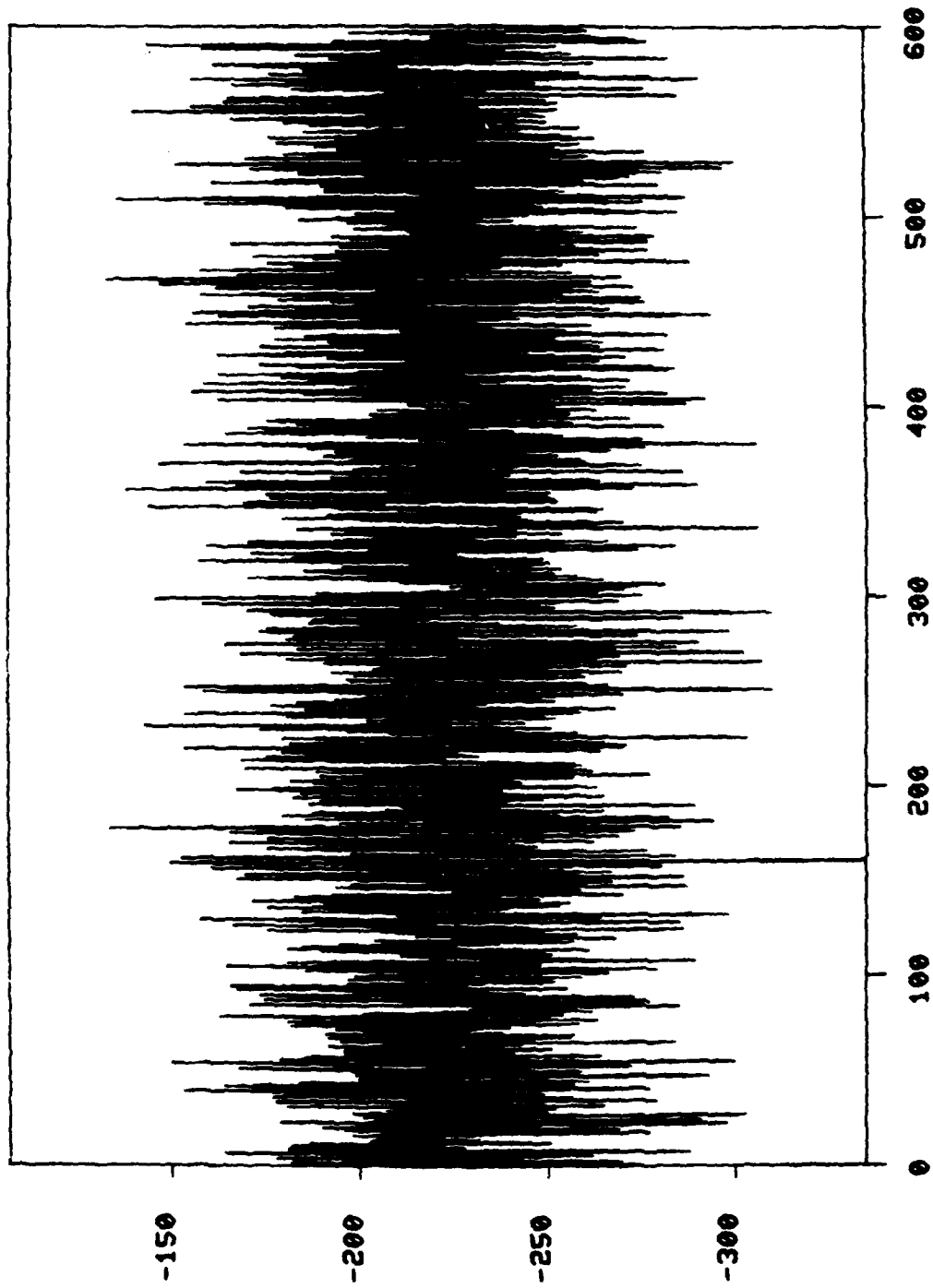
19 Helicopter operations over NAV CORP

CENTERPOINT - 45.22N 87.43W SCALE FACTOR +/- 3.80 DEGREES



20 Map of Great Lakes operations

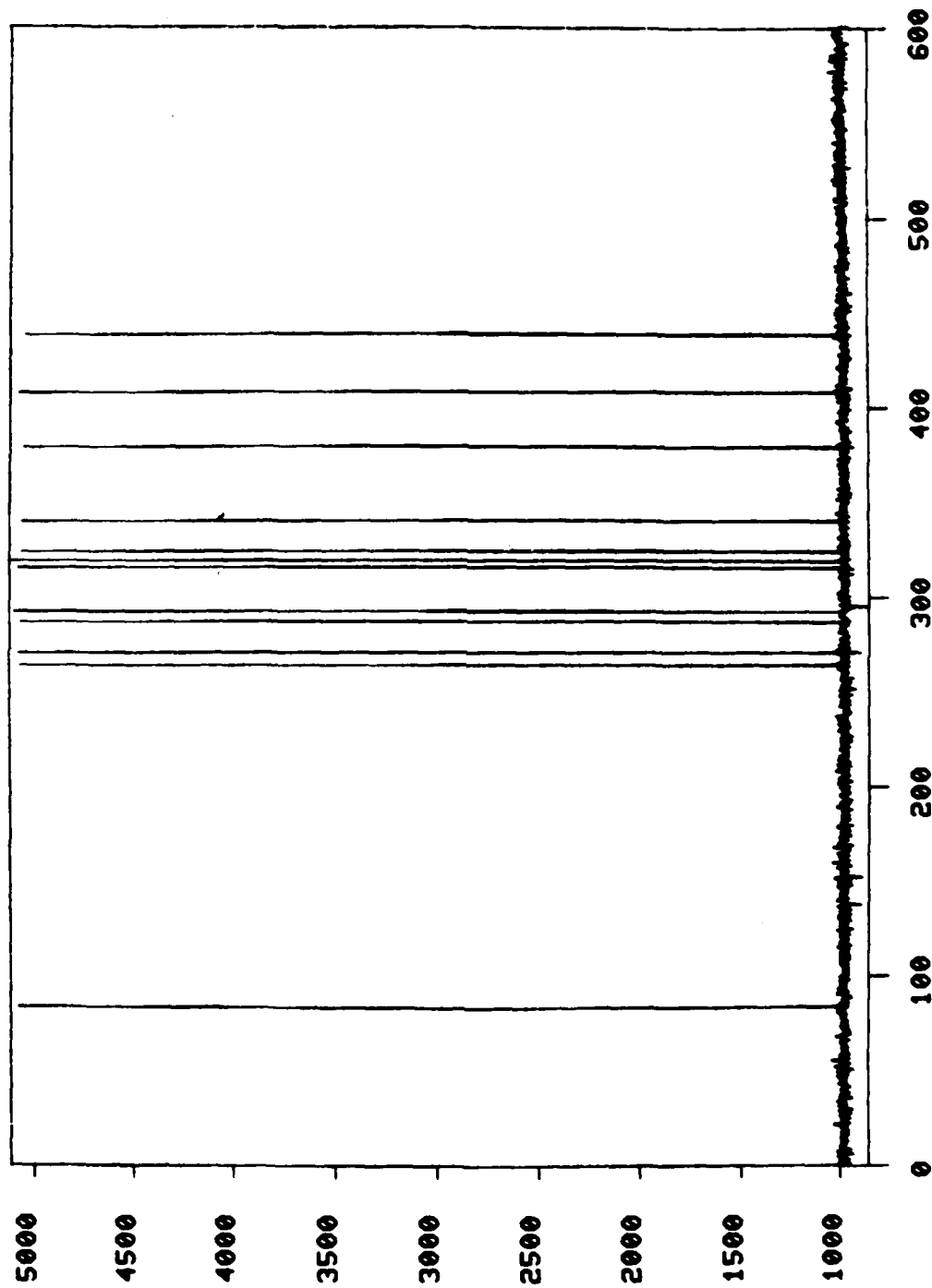
COL9  
RUN 70



21 Collins time history plot (1979 Run #70)

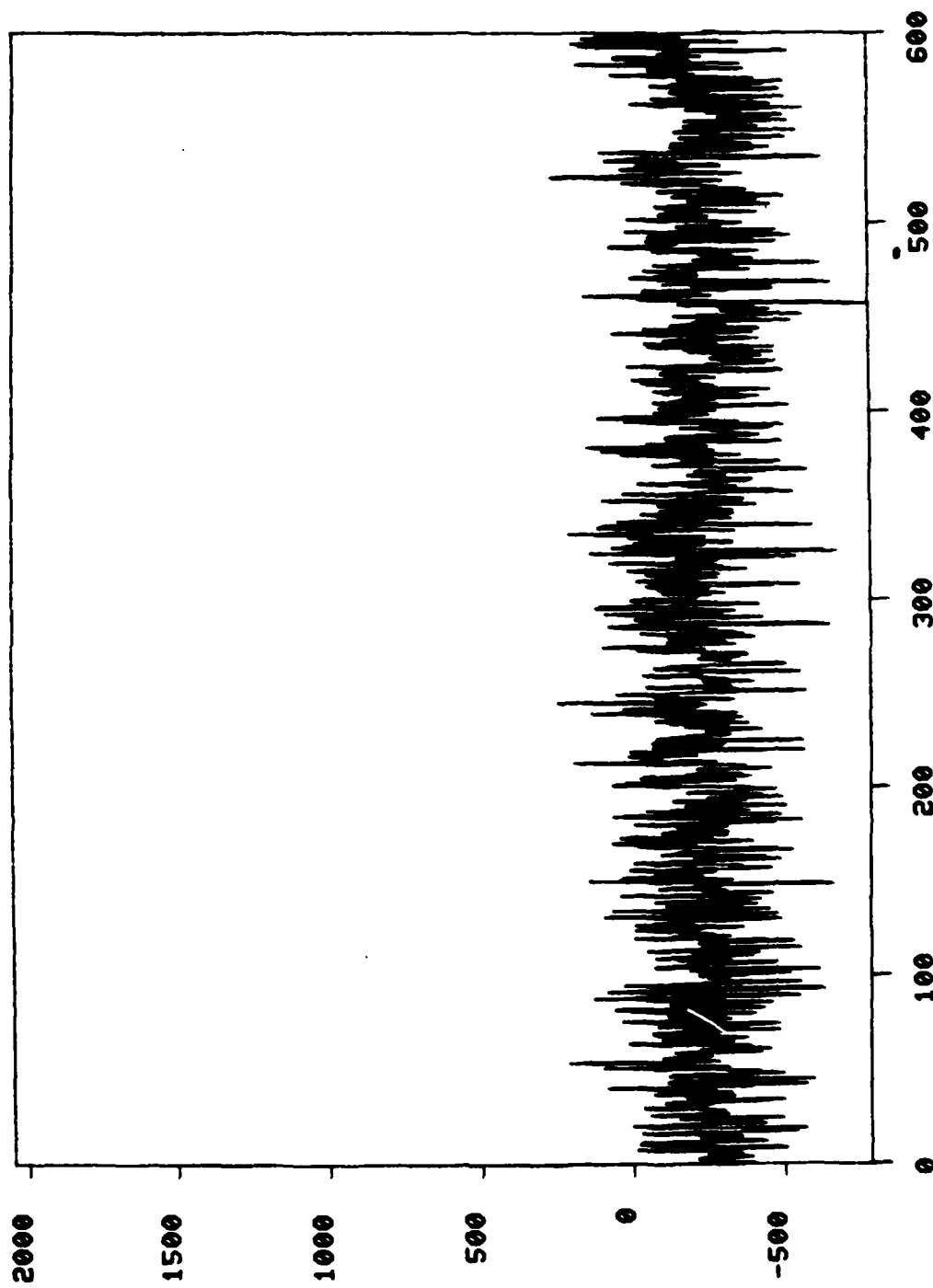


SL79  
RUN 70

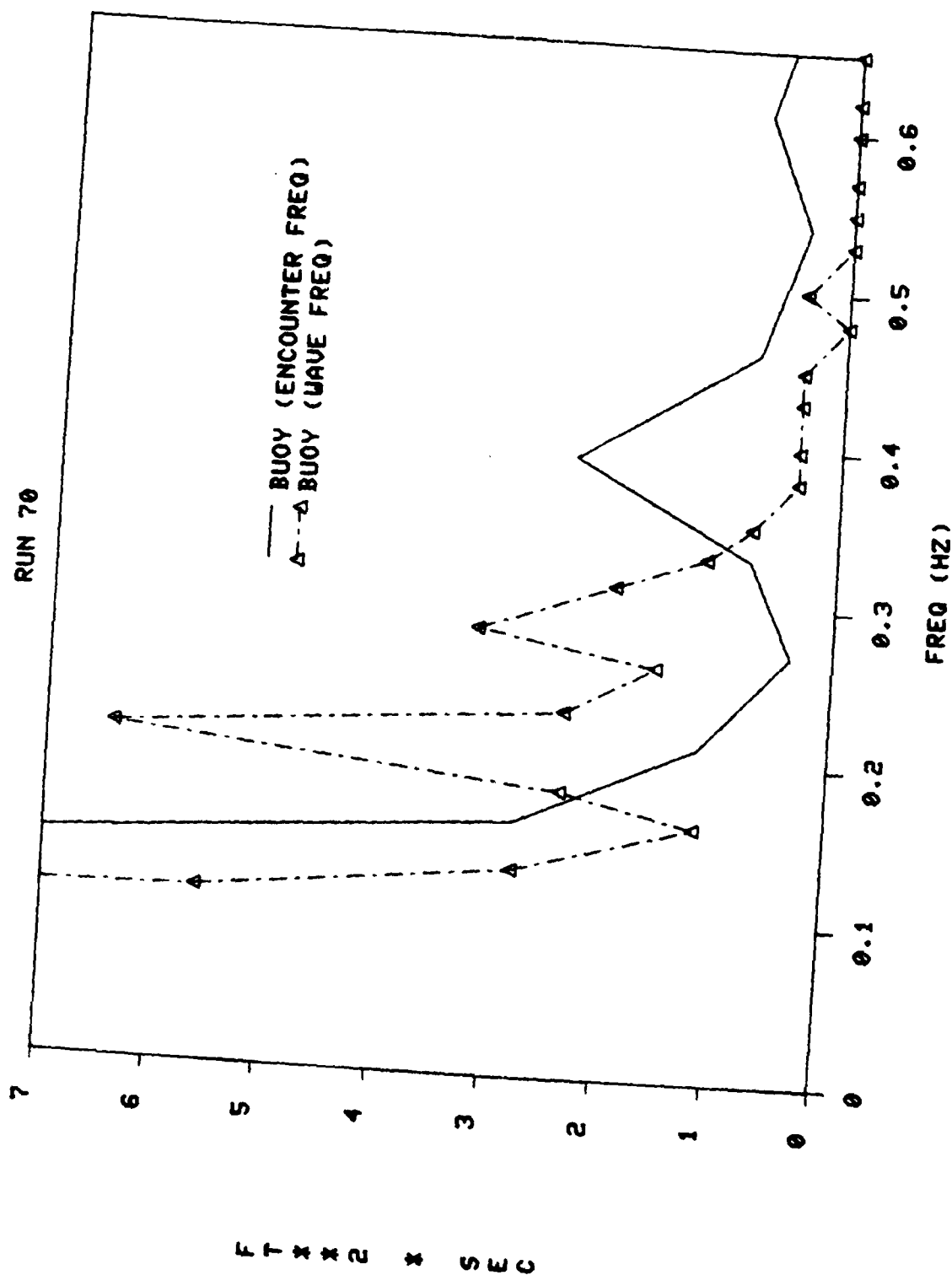


22 NRL microwave time history plot (1979 Run #70)

BU09  
RUN 70

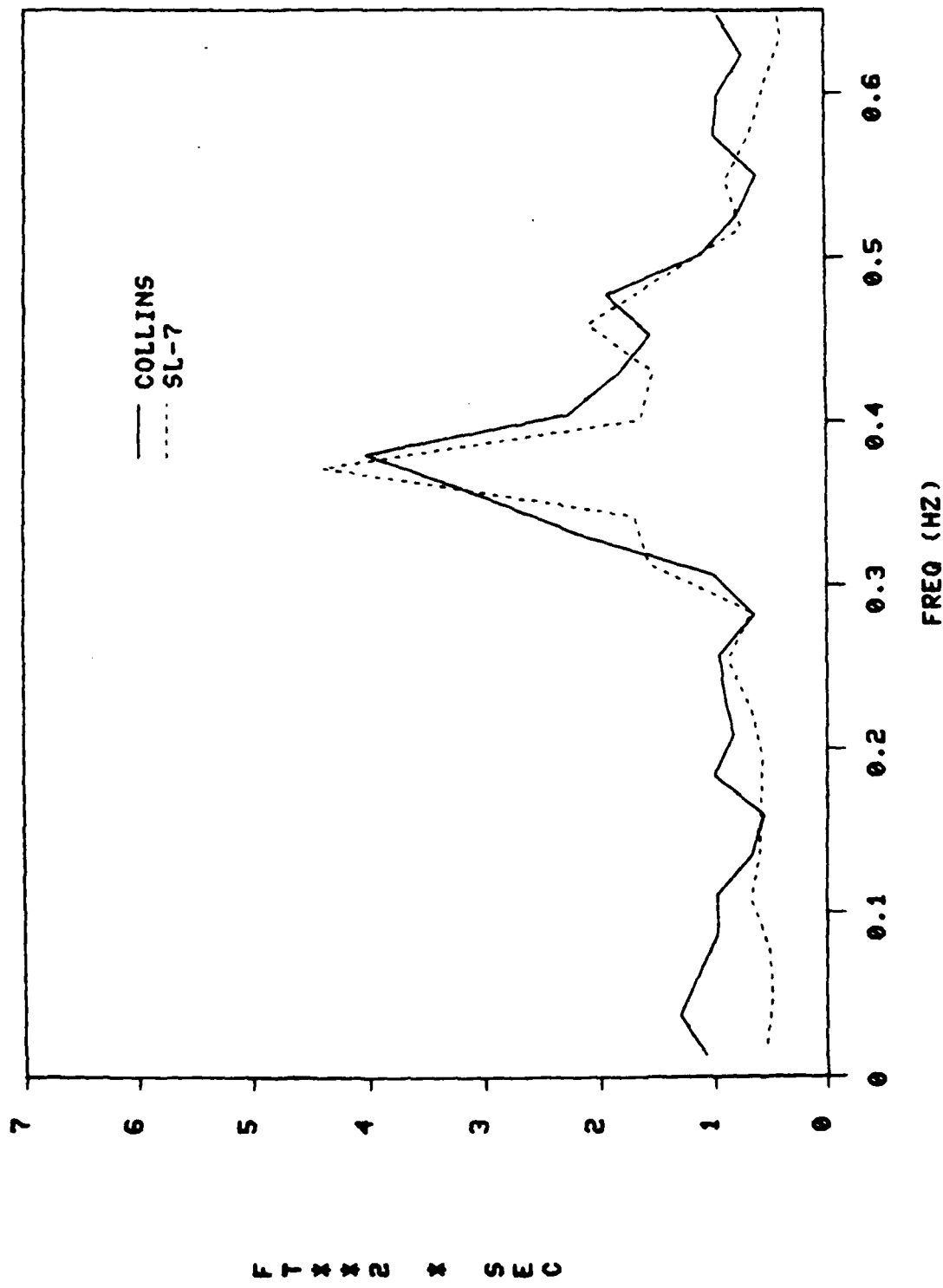


23 Wave buoy time history plot (1979 Run #70)

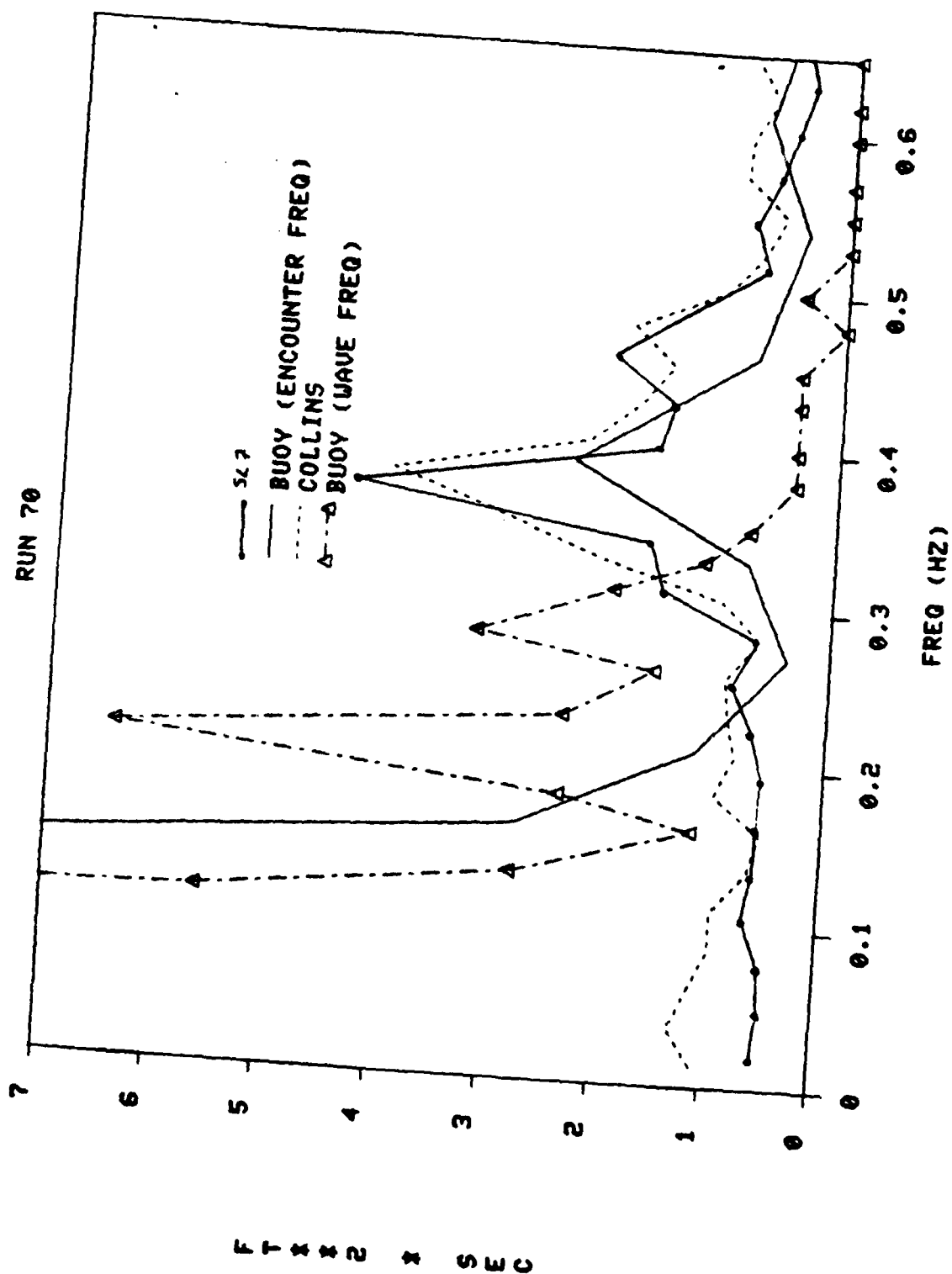


24 Buoy - Encounter vs. Wave frequency

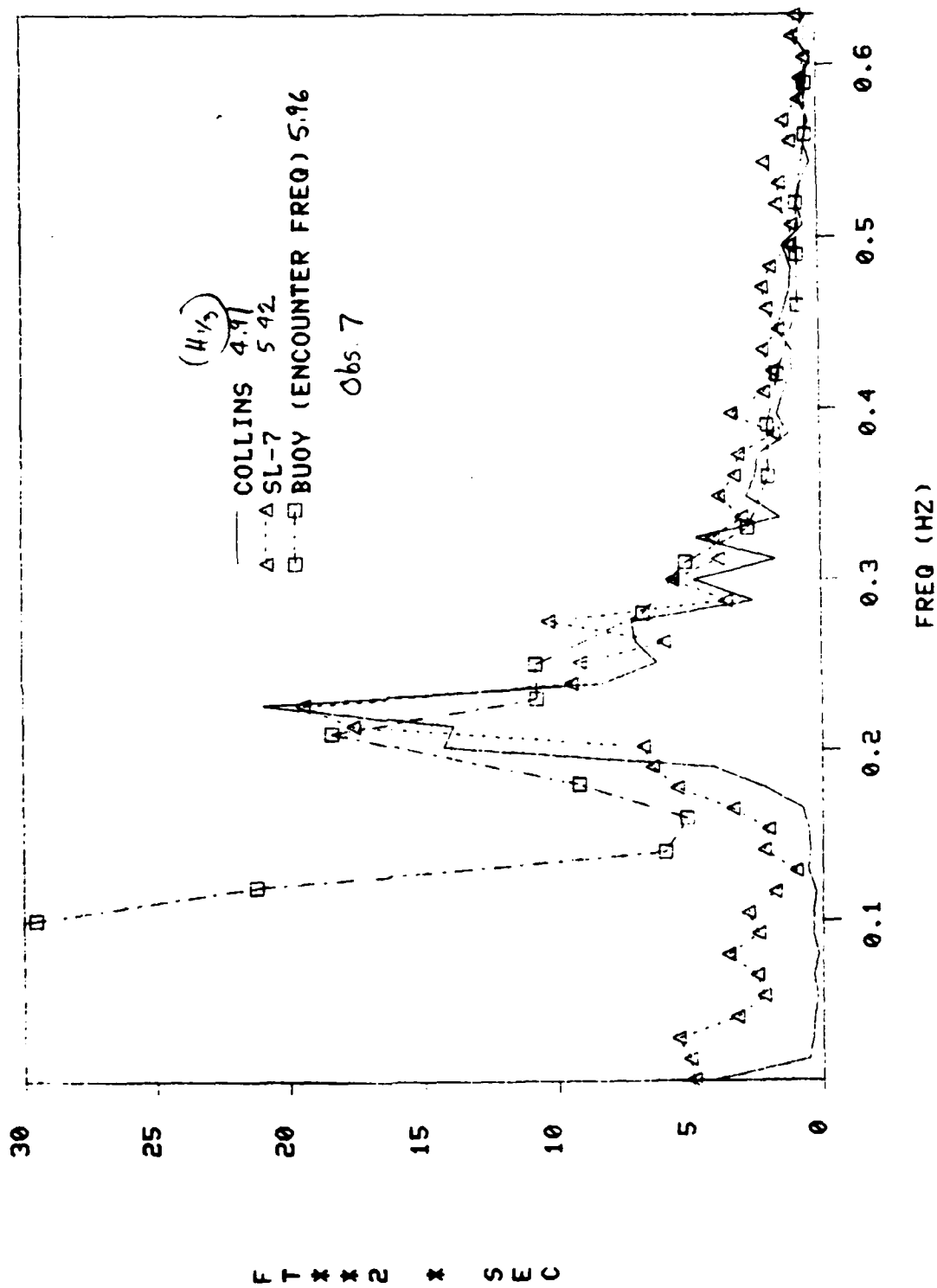
RUN 70



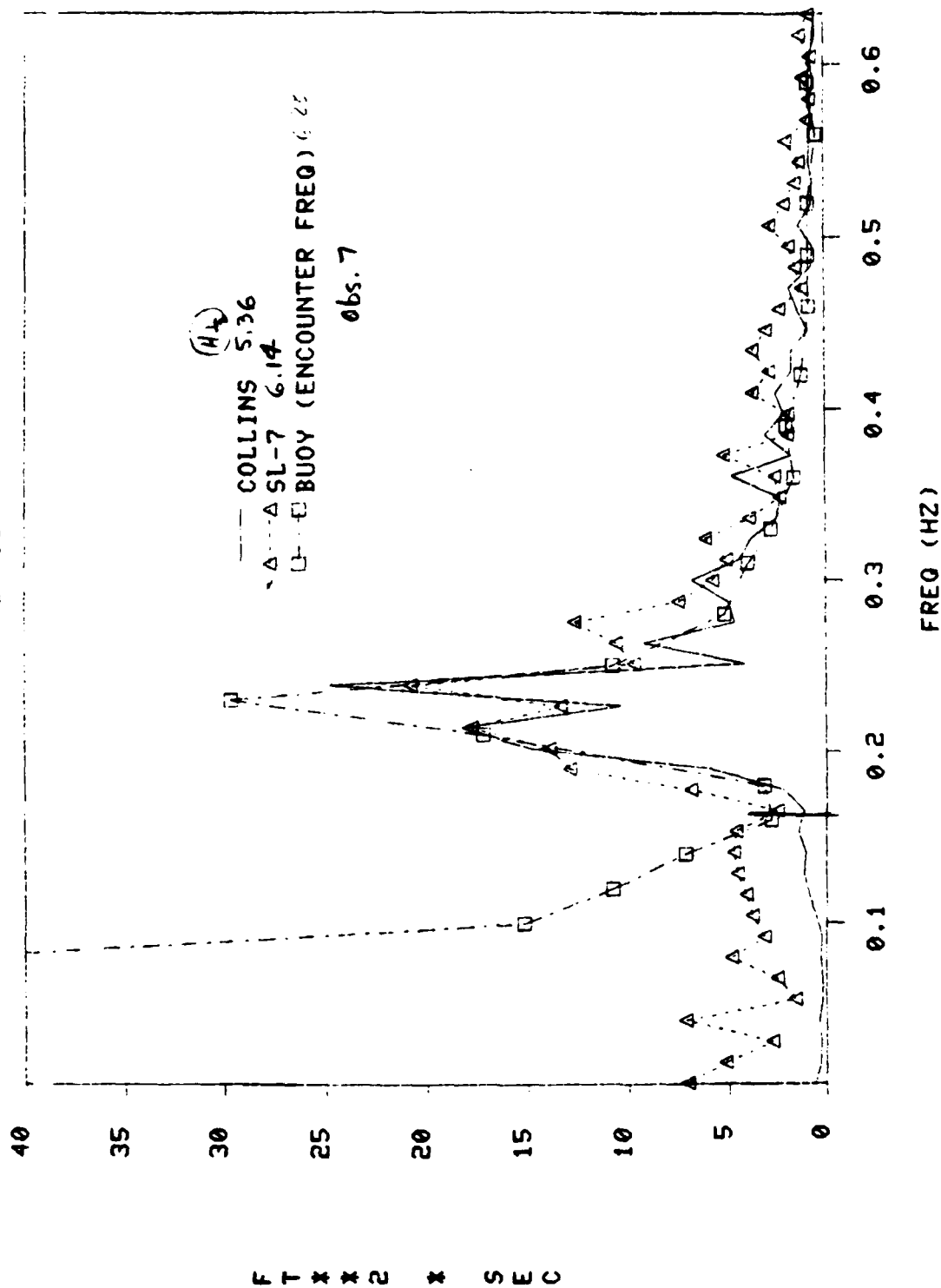
25 NRL microwave vs. Collins wave spectra



RUN CG-3

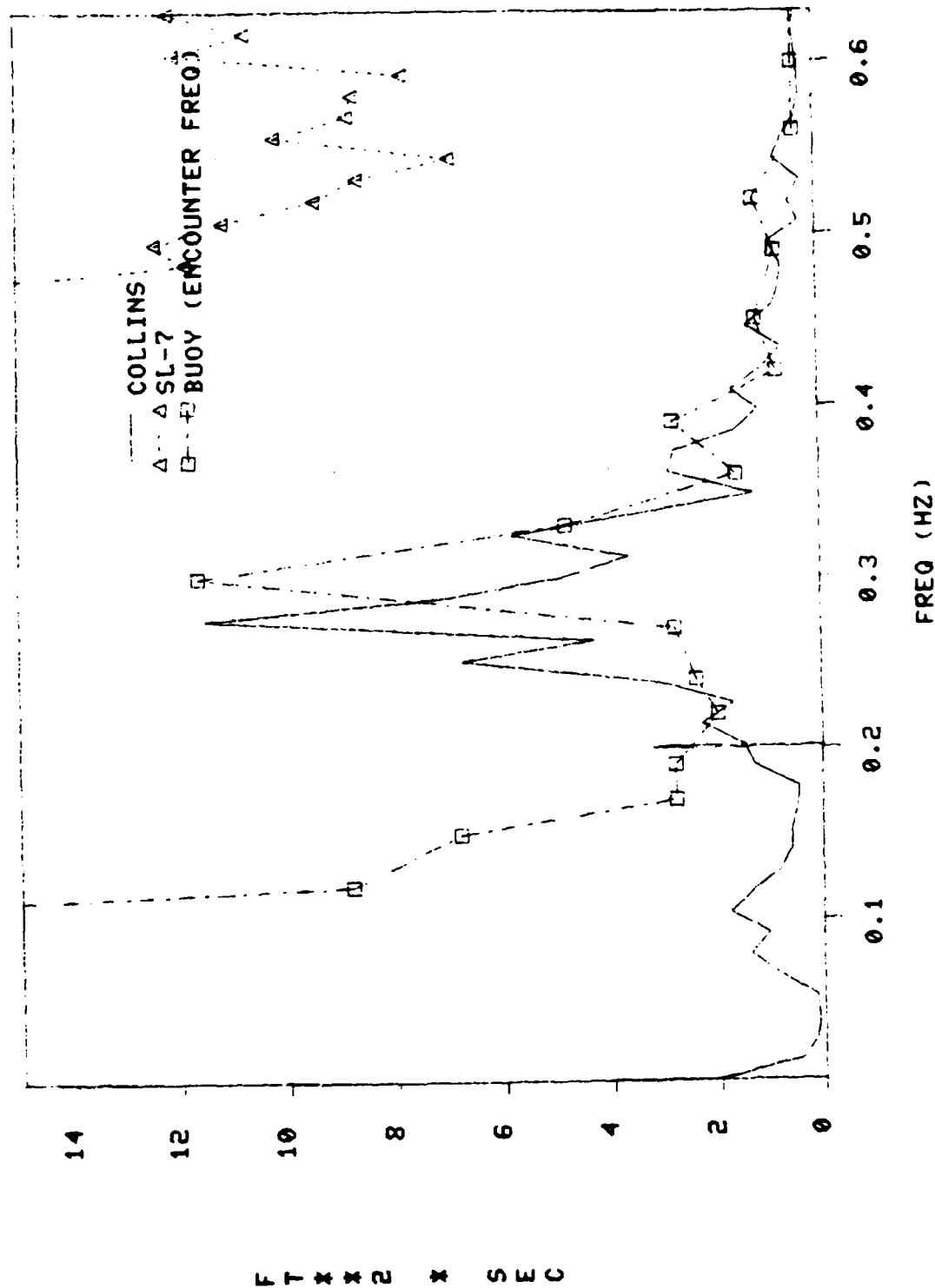


RUN CG-4



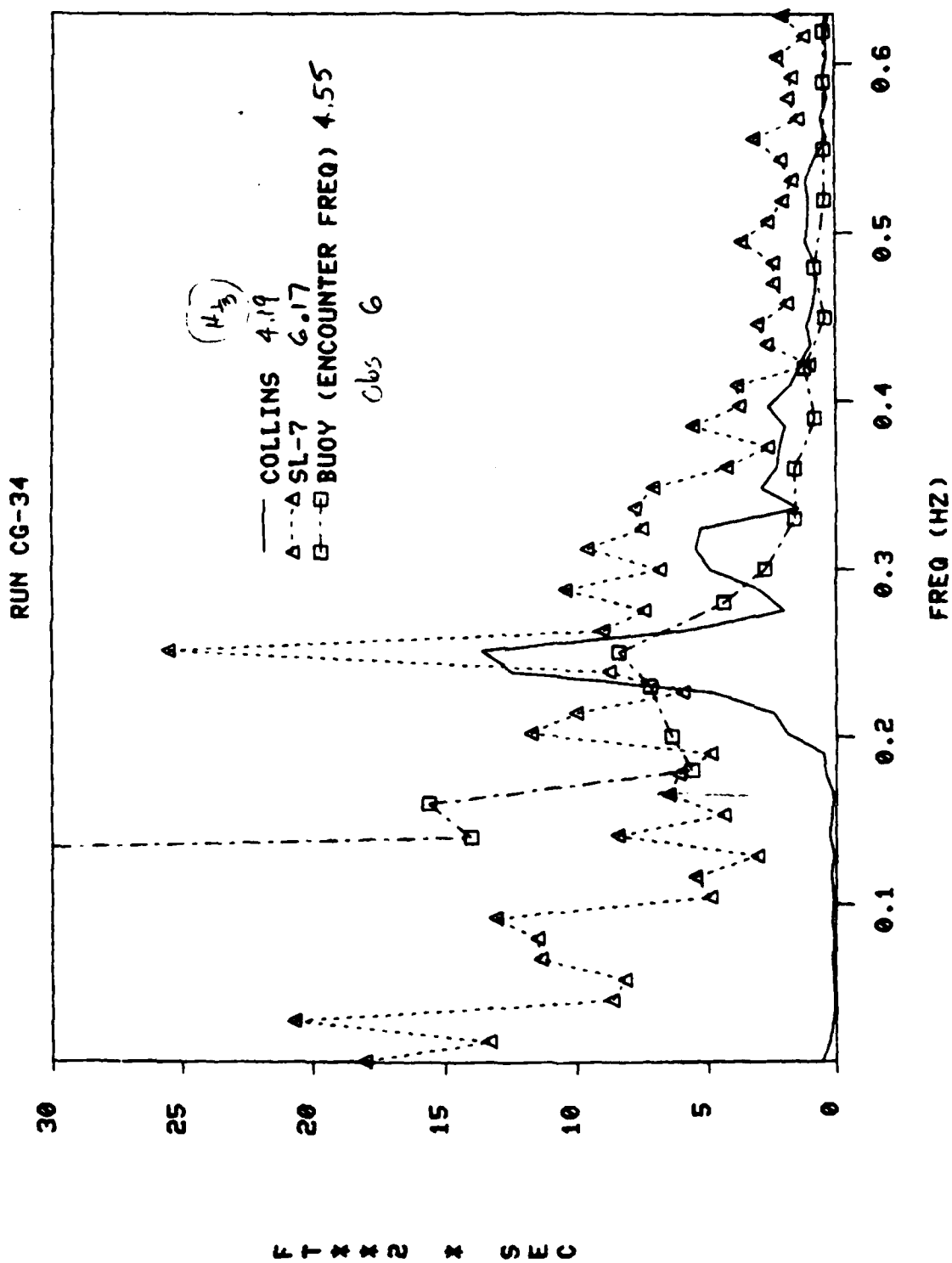
28 Wave spectra Collins, NRL microwave, buoy (1980 run #4)

RUN CG-7

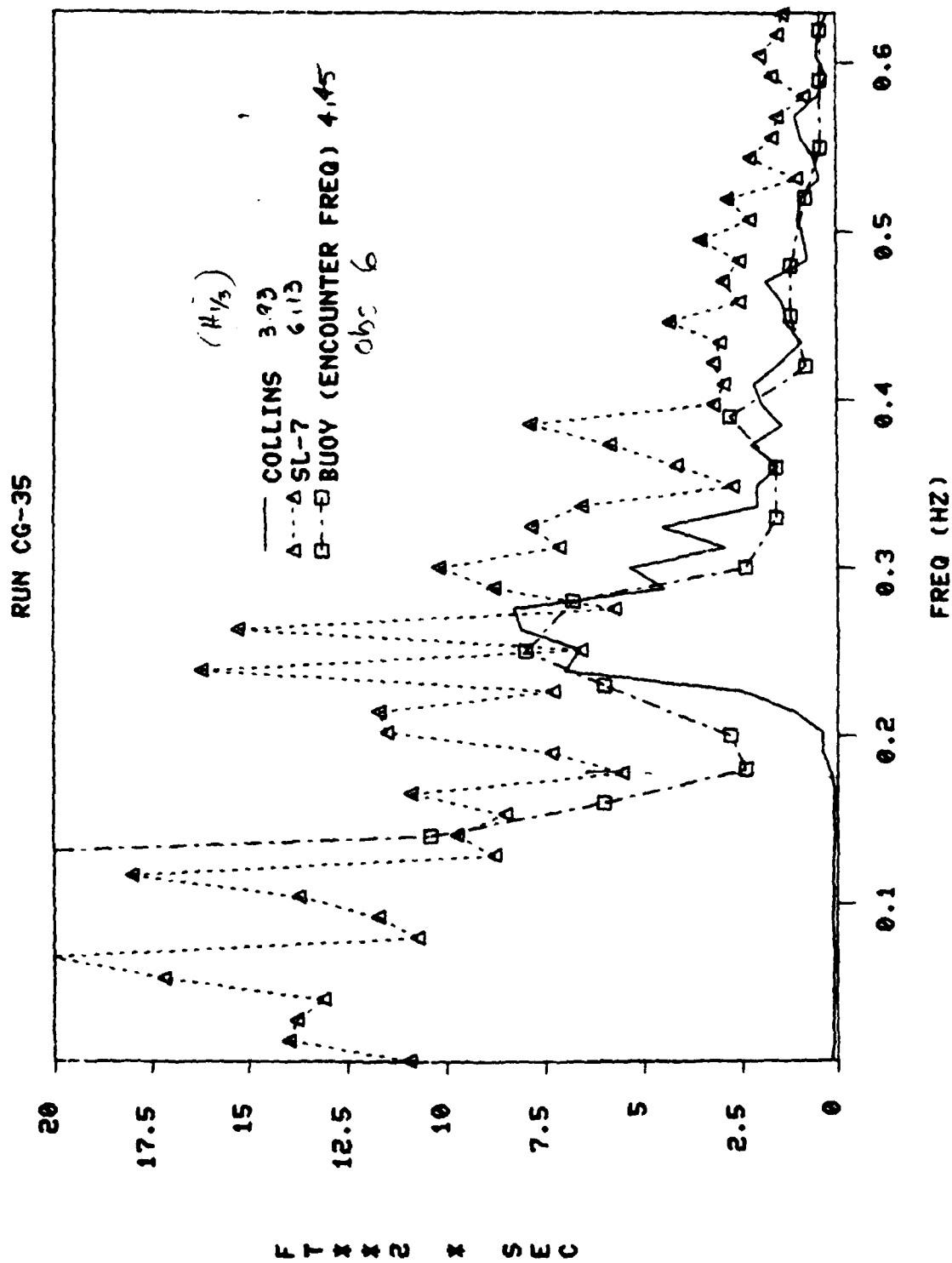


29 Wave spectra Collins, NRL microwave, buoy (1980 run #7)



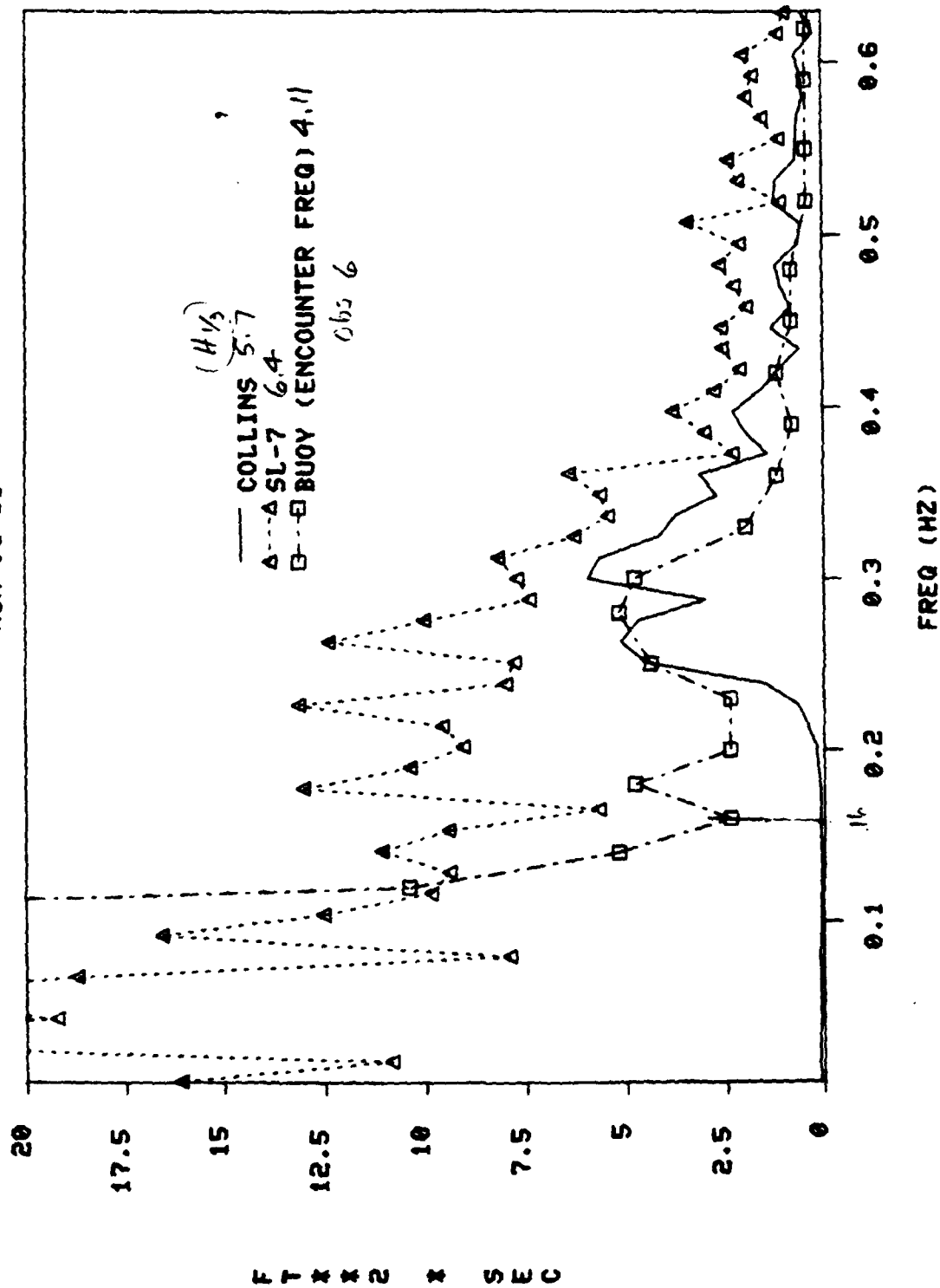


30 Wave spectra Collins, NRL microwave, buoy (1980 run #34)

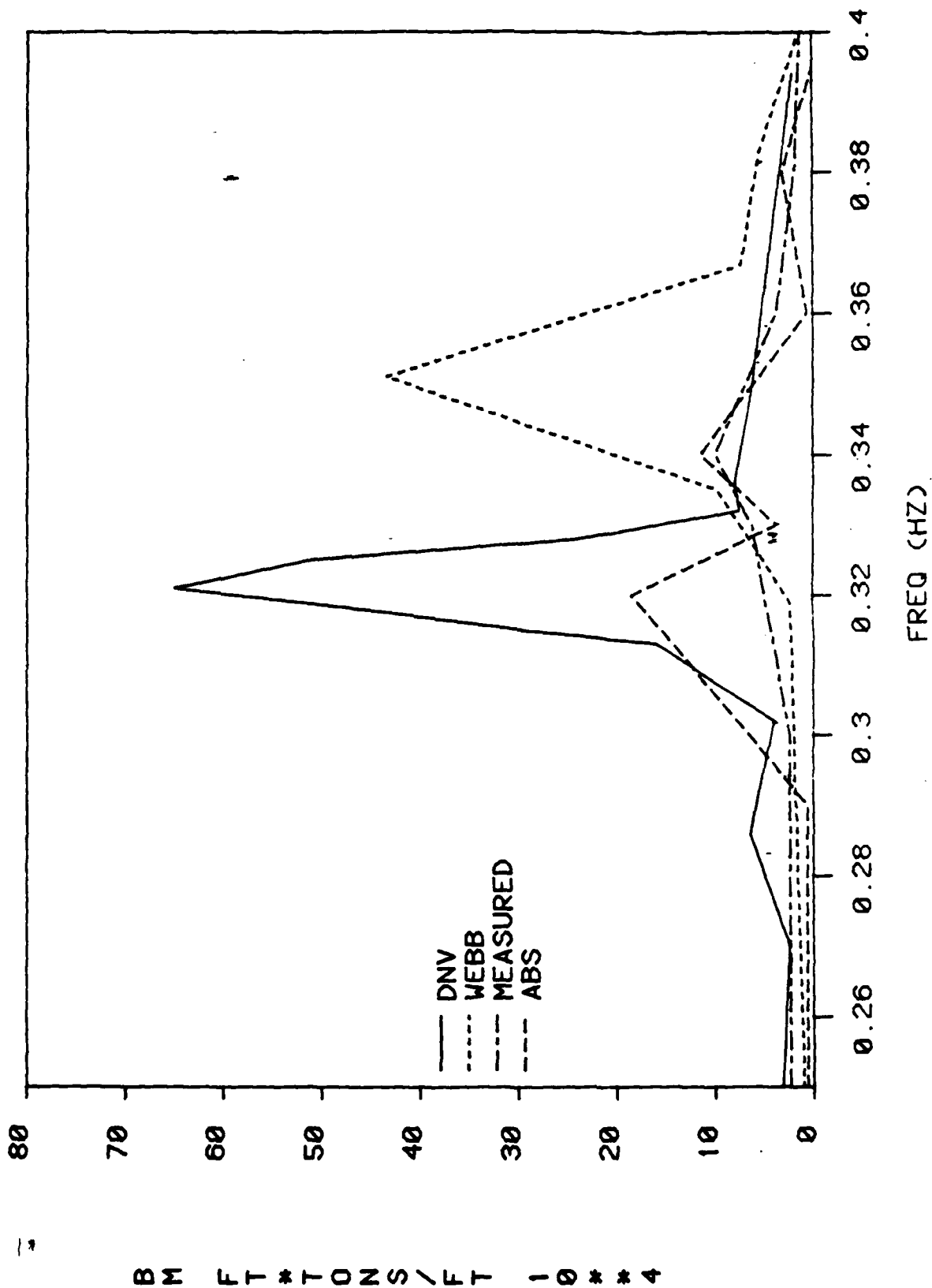


31 Wave spectra Collins, NRL microwave, buoy (1980 run #35)

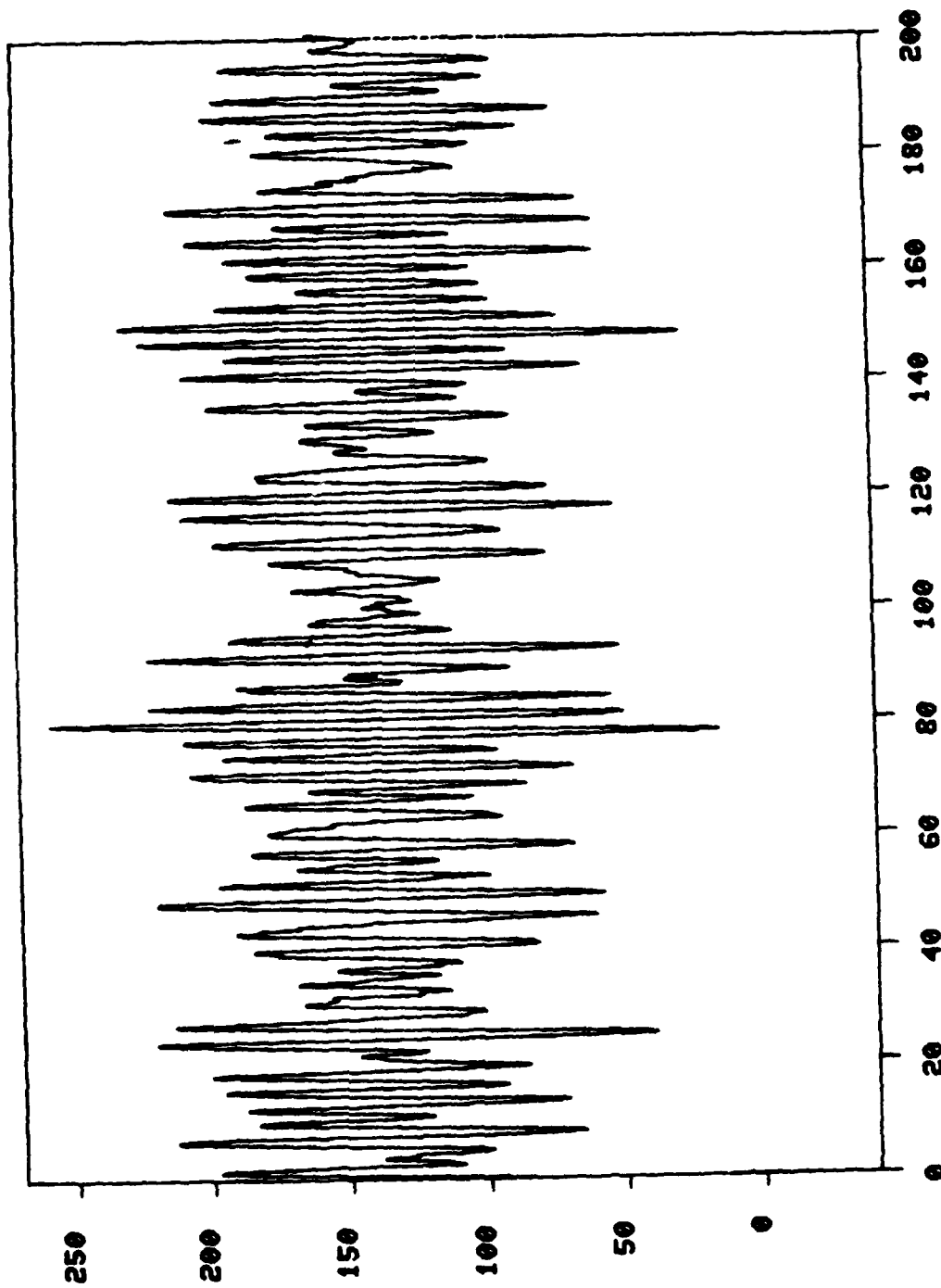
RUN CG-36



# RAO COMPARISON

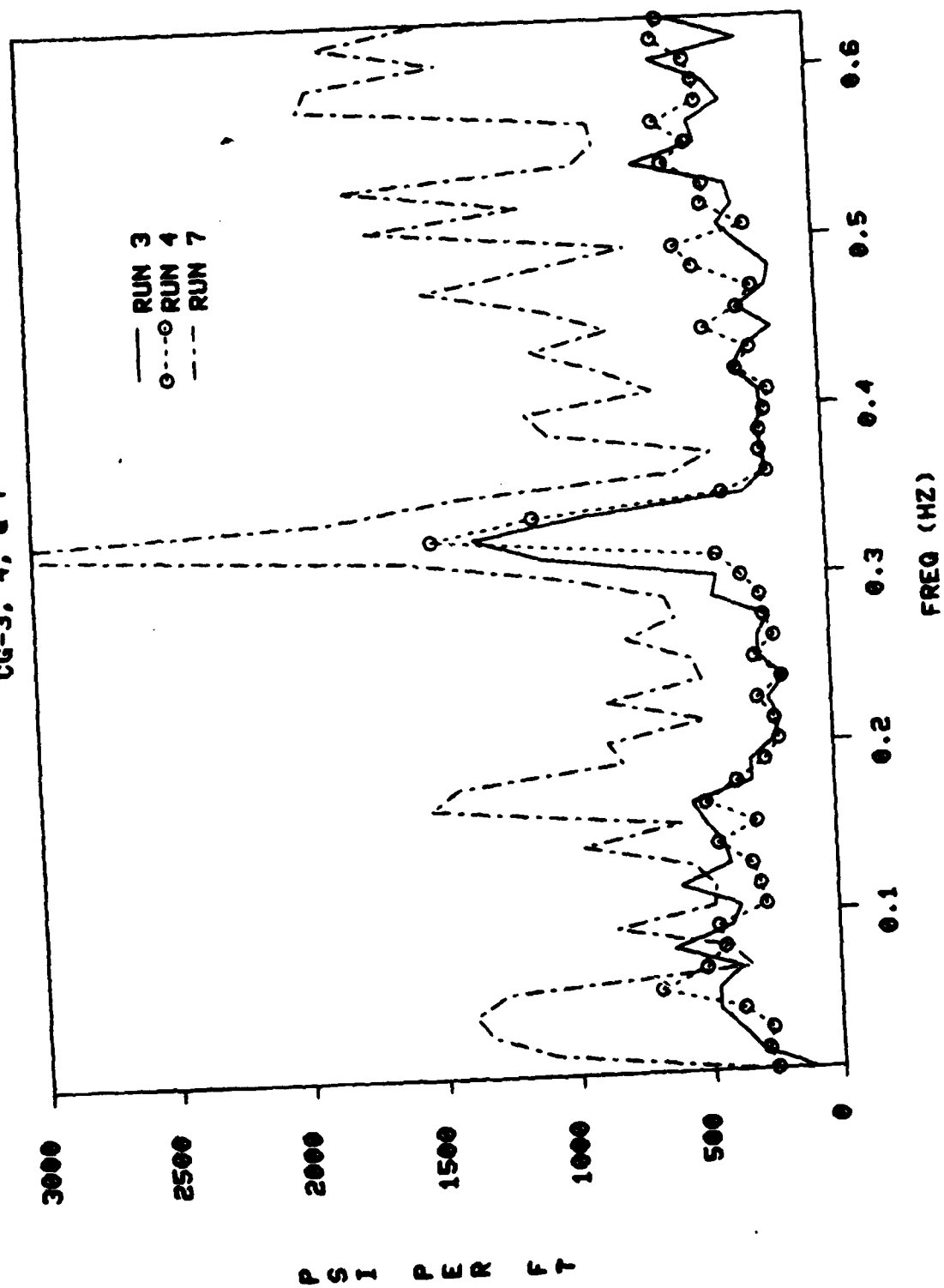


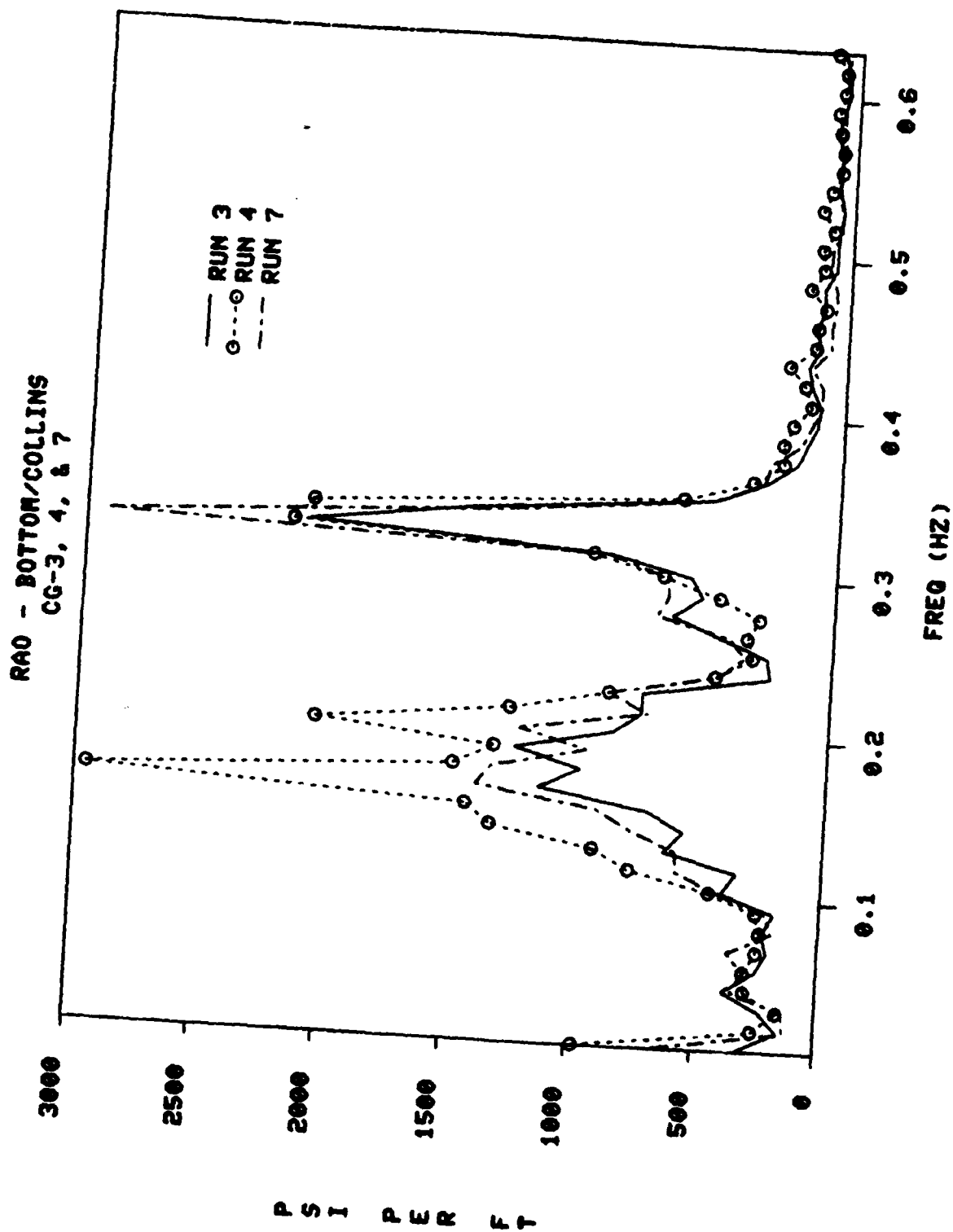
**BOTTOM STRESS  
RUN DT-77**

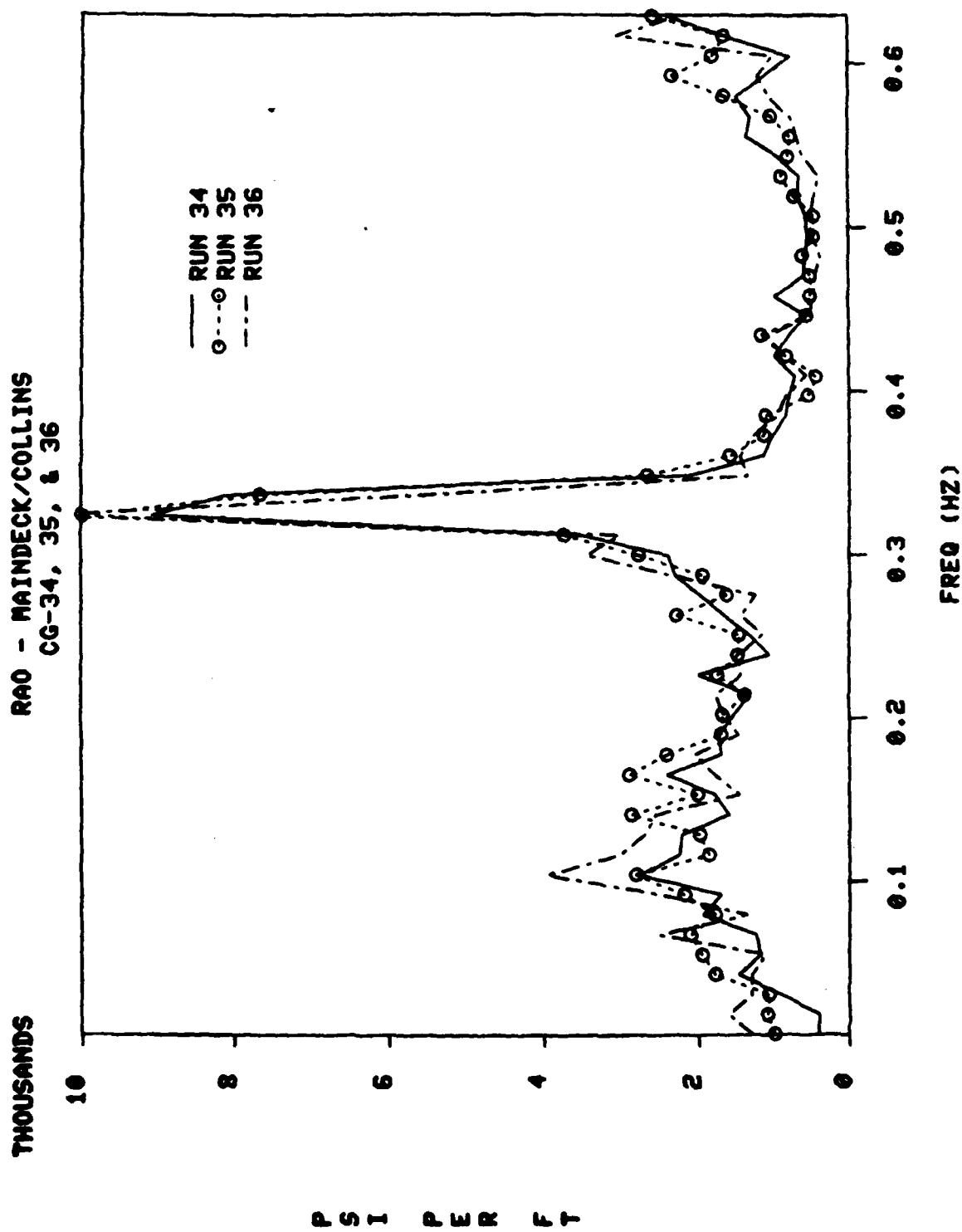


34 Strain gauge time history plot

RAO - MAINDECK/COLLINS  
CG-3, 4, & 7



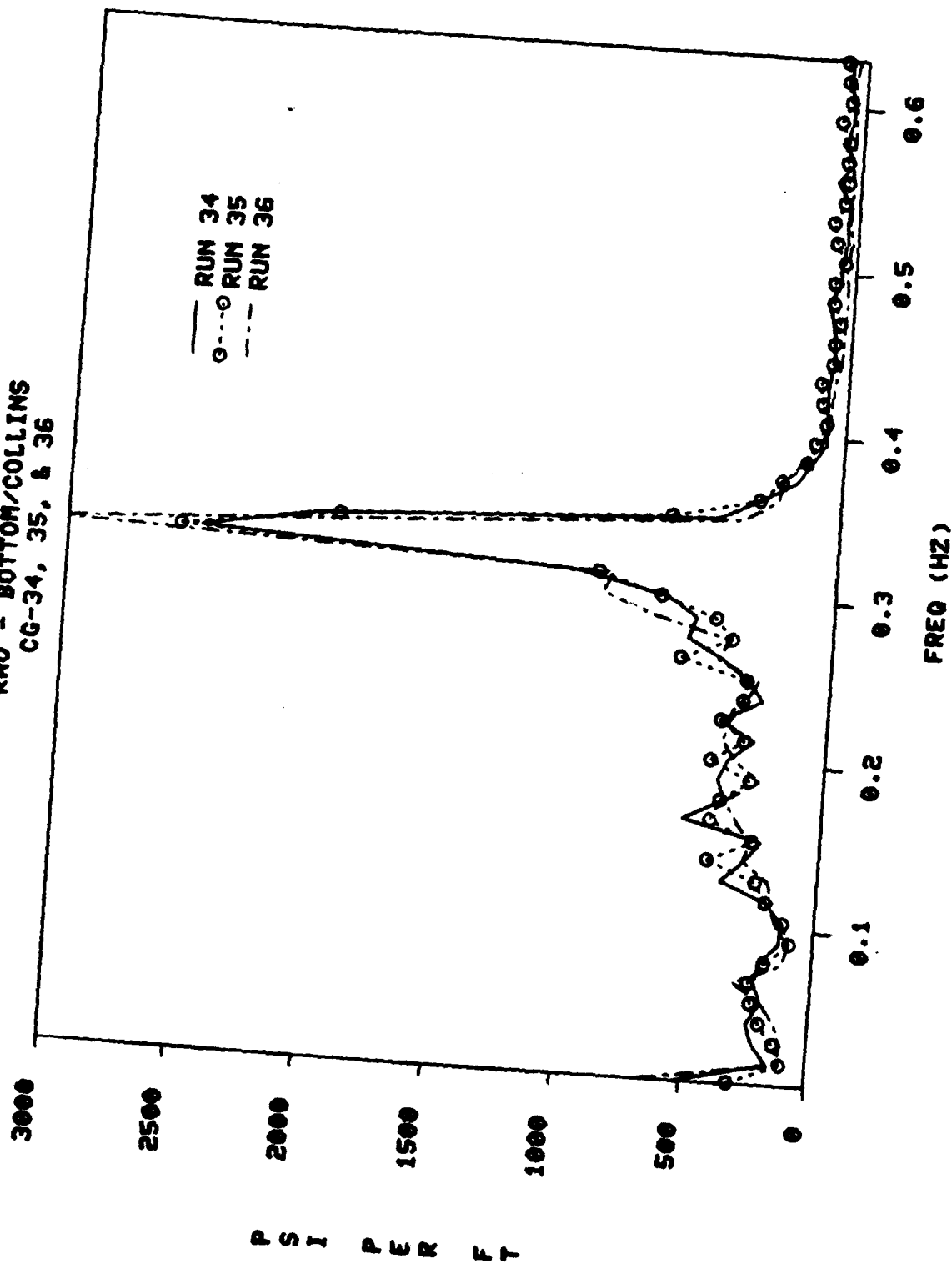




37 RAOs Maindeck/Collins (1980 runs 34,35,36)



RAO - BOTTOM/COLLINS  
CG-34, 35, & 36



38 RAOs Bottom/Collins (1980 runs 34,35,36)

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FILMED  
8